DESCRIPTION

METHOD OF ASSUMING ACTING POINT OF FLOOR REACTION FORCE TO BIPED WALKING MOBILE BODY AND METHOD OF ASSUMING JOINT MOMENT OF BIPED WALKING MOBILE BODY

5

Technical Field

The present invention relates to a method of estimating the position of a floor reaction force acting point of each leg of a biped walking mobile body, such as

10 a human being or a biped walking robot. The present invention further relates to a method of estimating the moment acting on a joint of a leg of the biped walking mobile body by using the estimated value of the position of the floor reaction force acting point.

15

Background Art

To control an operation of, for example, a walking aid apparatus for assisting a human being in walking or to control a traveling motion of a biped walking robot, it is

20 necessary to successively grasp the floor reaction forces acting on legs of the human being or the biped walking robot (to be more specific, the forces from a floor that act on ground contact portions of the legs) and the positions of floor reaction force acting points. Grasping

25 the floor reaction forces and the floor reaction force acting points makes it possible to grasp moments or the like acting on joints of the legs of the biped walking

mobile body, and to decide desired auxiliary forces of the walking aid apparatus or desired drive torques or the like of joints of the biped walking robot on the basis of the grasped moments or the like.

5   As a technique for grasping the floor reaction forces, one disclosed in, for example, Japanese Unexamined Patent Application Publication No. 2000-249570, has been known. According to this technique, a floor reaction force of each leg is grasped as a resultant value (linear 10 combination) of a plurality of trigonometric functions having mutually different cycles of 1/n (n = 1, 2, ...) of a walking cycle, because the time-dependent change waveform of a floor reaction force of each leg periodically changes during steady walking of a biped 15 walking body. According to this technique, however, the positions of floor reaction force acting points cannot be grasped, making the technique inadequate for grasping moments acting on the joints of legs of the biped walking mobile body.

20   There has been also known a technique in which a biped walking mobile body is walked on a force plate installed on a floor so as to grasp floor reaction forces and the positions of floor reaction force acting points on the basis of the outputs of the force plate (refer to, for 25 example, Japanese Unexamined Patent Application Publication No. 2001-29329). This technique, however, presents a problem in that the floor reaction forces and

the positions of floor reaction force acting points can be grasped only in an environment wherein a force plate is installed, so that the technique cannot be applied to the walking of a biped walking mobile body in a normal

5   environment.

Accordingly, the present applicant has previously proposed in, for example, Japanese Patent Application No. 2002-18798 (Japanese Unexamined Patent Application Publication No. 2003-220584), a technique that permits

10   real-time estimation of the positions of floor reaction force acting points. This technique uses the fact that the inclination angle of a thigh of each leg or the bending angle of a knee joint has a relatively high correlation with the position of a floor reaction force

15   acting point with respect to the ankle of each leg (the positional vector of a floor reaction force acting point, using the ankle as the reference). More specifically, according to the technique, the correlation data (e.g., data tables or arithmetic expressions) showing the

20   correlation between the inclination angles of thighs or the bending angles of knee joints and the positions of floor reaction force acting points is created and retained in a memory beforehand, and the positions of floor reaction force acting points are estimated from the

25   correlation data and the inclination angles of thighs or the bending angles of knee joints measured while a biped walking mobile body is walking.

However, further experiment and study by the inventors of the present application have revealed that the correlation between the inclination angles of thighs or the bending angles of knee joints and the positions of floor reaction force acting points is influenced by the walking speed or the like of a biped walking mobile body and further influenced by the motion modes of a biped walking mobile body, such as a level-ground walking mode, a staircase walking mode, and a slope walking mode. Hence, in order to properly estimate the positions of the floor reaction force acting points by the aforementioned technique, it has been necessary to prepare a plurality of types of the above correlation data for each walking speed or motion mode of the biped walking mobile body and to retain them in a memory beforehand, inconveniently taking up a major part of the capacity of the memory. There has been another inconvenience in that, when a motion mode is changed over, discontinuity in position of a floor reaction force acting point estimated on the basis of another correlation data is likely to occur before or after the changeover, resulting in a discontinuously changed estimated value of a joint moment when the estimated position of the floor reaction force acting point is used to estimate the joint moment.

The present invention has been made in view of the above background, and it is an object of the present invention to provide a floor reaction force acting point

estimating method that makes it possible to grasp, in real time, the position of a floor reaction force acting point by a relatively simple technique without using a plurality of types of correlation data, and that is particularly

5   suited for grasping the position of a floor reaction force acting point related to a human being as a biped walking mobile body.

      Moreover, it is another object of the present invention to provide a method of estimating a joint moment

10   of the biped walking mobile body that makes it possible to grasp, in real time, the moment acting on a joint, such as a knee joint of a leg, by using the aforesaid estimated value of a floor reaction force acting point.

15   Disclosure of Invention

      The findings obtained by great efforts, including a variety of experiments, made by the inventors of the present application, indicate that, when a biped walking mobile body, such as a human being, is walking on a level

20   ground, for example, the horizontal position of the floor reaction force acting point of each leg in contact with the ground is usually substantially equal to one of the positions of the horizontal position of the center of gravity of the biped walking mobile body, the horizontal

25   position of the metatarsophalangeal joint of the foot of the leg (the joint of the thumb root of the foot), and the horizontal position of the ankle joint of the leg,

depending on which place of the foot of the leg is in contact with the ground, independently of the moving speed or the motion mode or the like of the biped walking mobile body. To be more specific, on each leg, if the leg is in

5   contact with the ground at the place substantially directly below the metatarsophalangeal joint (a place adjacent to the toe) with the heel side of the foot not in contact with the ground, then the horizontal position of the floor reaction force acting point related to the leg

10   will be substantially equal to the horizontal position of the metatarsophalangeal joint, or if the leg is in contact with the ground at the place substantially directly below the ankle joint (a place adjacent to the heel) with the toe side of the foot not in contact with the ground, then,

15   the horizontal position of the floor reaction force acting point related to the leg will be substantially equal to the horizontal position of the ankle joint. Further, if both the place adjacent to the toe of the foot and the place adjacent to the heel of the foot are in contact with

20   the ground (substantially the entire sole of the foot is in contact with the ground), then the horizontal position of the floor reaction force acting point related to the leg will be substantially equal to the horizontal position of the center of gravity of the biped walking mobile body

25   in most cases. Thus, the horizontal positions of the floor reaction force acting points of each leg can be estimated by successively grasping the center of gravity

of the biped walking mobile body and the positions
(especially the horizontal positions) of the ankle joint
and the metatarsophalangeal joint of the leg and also by
grasping which place of the foot of the leg in contact

5   with the ground is in contact with the ground. Moreover,
the vertical position of the floor reaction force acting
point of each leg in contact with the ground, especially
the vertical position relative to an ankle joint, is
defined by the vertical distance from the ankle joint to

10   the ground contact surface of the leg.

Thus, to fulfill the objects described above,
according to a method of estimating a floor reaction force
acting point of a biped walking mobile body in accordance
with the present invention, i.e., a method of successively

15   estimating the position of the floor reaction force acting
point of each leg of a biped walking mobile body, in the
sole of the foot of each leg of the biped walking mobile
body, a first ground contact sensor and a second ground
contact sensor that output ground contact detection

20   signals based on the contact or no contact of a place
directly below an ankle joint of a leg and a place
directly below a metatarsophalangeal joint of the foot of
the leg, respectively, are provided. The method includes
a first step for successively grasping the position of the

25   center of gravity of the biped walking mobile body, the
position of the ankle joint of each leg, and the position
of the metatarsophalangeal joint of the foot of the leg,

respectively, and also successively grasping the vertical distance from the ankle joint to a ground contact surface of each leg in contact with the ground while the biped walking mobile body is in motion, and

5   a second step for successively estimating selectively the horizontal position of one of the center of gravity, the ankle joint of the leg, and the metatarsophalangeal joint of the leg, the positions thereof having been determined in the first step, as the

10 horizontal position of the floor reaction force acting point of the leg on the basis of at least the combination of contact or no contact indicated by a ground contact detection signal of the first ground contact sensor and contact or no contact indicated by a ground contact

15 detection signal of the second ground contact sensor for each leg in contact with the ground while the biped walking mobile body is in motion, and also successively estimating the vertical position of the floor reaction force acting point of the leg as the position apart

20 vertically downward from the ankle joint by the vertical distance from the ankle joint to the ground contact surface of the leg determined in the first step.

According to the method of estimating a floor reaction force acting point in accordance with the present

25 invention, the position of the center of gravity of a biped walking mobile body, the position of the ankle joint of each leg, and the position of the metatarsophalangeal

joint of the foot of the leg are successively grasped respectively, and the horizontal position of one of the center of gravity, the ankle joint, and the metatarsophalangeal joint is selectively estimated

5 successively as the horizontal position of the floor reaction force acting point of the leg on the basis of the combination of contact or no contact at respective places, which is indicated by ground contact detection signals of the first and the second ground contact sensors provided

10 at two places (the place directly below the ankle joint and the place directly below the metatarsophalangeal joint) of the sole of the foot of each leg. This arrangement allows the horizontal position of a floor reaction force acting point to be estimated without using

15 a data table, or map data or the like. Moreover, the vertical distance from the ankle joint to a ground contact surface (floor surface) of each leg in contact with the ground is successively grasped in the first step, thereby estimating the position vertically apart downward from the

20 ankle joint by that vertical distance as the vertical position of the floor reaction force acting point, so that it is possible to estimate the vertical position of a floor reaction force acting point without using a data table, or map data or the like.

25 Thus, according to the method of estimating a floor reaction force acting point in accordance with the present invention, the position of a floor reaction force acting

point can be grasped in real time by a relatively simple technique without using a plurality of types of correlation data.

The method of estimating a floor reaction force acting point in accordance with the present invention makes it possible to grasp the position of the center of gravity, the position of an ankle joint, and the position of a metatarsophalangeal joint by detecting, for example, the inclination angle of a body by a gyro-sensor or an acceleration sensor and by detecting the bending angle of a joint of each leg by a potentiometer or the like, and then by using the detected inclination angle of the body, the detected bending angle of the joint of the leg, and a rigid link model representing a biped mobile body in the form of a rigid linkage assembly.

According to the method of estimating a floor reaction force acting point in accordance with the present invention, basically, if a ground contact detection signal of the first ground contact sensor of each leg is a signal indicating contact with the ground and a ground contact detection signal of the second ground contact sensor of the leg is a signal indicating no contact with the ground, then the horizontal position of the ankle joint of the leg may be estimated as the horizontal position of a floor reaction force acting point of the leg, or if a ground contact detection signal of the first ground contact sensor of each leg is a signal indicating no contact with

the ground and a ground contact detection signal of the
second ground contact sensor of the leg is a signal
indicating contact with the ground, then the horizontal
position of the metatarsophalangeal joint of the leg may

5   be estimated as the horizontal position of a floor
reaction force acting point of the leg, or if ground
contact detection signals of both the first ground contact
sensor and the second ground contact sensor of each leg
are signals indicating contact with the ground, then the

10   horizontal position of the center of gravity may be
estimated as the horizontal position of a floor reaction
force acting point of the leg.

However, depending on the motion mode or the like
of a biped walking mobile body, if ground contact

15   detection signals of both the first ground contact sensor
and the second ground contact sensor of each leg are
signals indicating contact with the ground, i.e., the
place directly below the ankle joint (the sole on the heel
side) and the place directly below the metatarsophalangeal

20   joint (the sole on the toe side) are in contact with the
ground (including contact that hardly produces a load),
then a situation may occur in which the position of the
center of gravity of the biped walking mobile body is
behind the position of the ankle joint of the leg in

25   contact with the ground or before the position of the
metatarsophalangeal joint in the advancing direction of
the biped walking mobile body. In such a case, the

horizontal position of the center of gravity deviates from the ground contact surface of the leg. Hence, if the horizontal position of the center of gravity is estimated as the horizontal position of a floor reaction force

5   acting point, then the estimating position will be inaccurate with respect to the horizontal position of a normal floor reaction force acting point that should exist within a ground contact surface of the leg. Further, if the center of gravity of the biped walking mobile body

10   exists behind the position of the ankle joint of the leg in contact with the ground, then the floor reaction force related to the leg is generally concentrated on a place adjacent to the heel of the foot of the leg (that is, a place in the vicinity of the first ground contact sensor).

15   Further, if the center of gravity of the biped walking mobile body exists before the position of the metatarsophalangeal joint of the foot of the leg in contact with the ground, then the floor reaction force related to the leg is generally concentrated on a place

20   adjacent to the toe of the leg (that is, a place in the vicinity of the second ground contact sensor).

Therefore, according to the method of estimating a floor reaction force acting point in accordance with the present invention, to estimate the horizontal position of

25   the floor reaction force acting point in the second step, on each leg in contact with the ground, preferably, if a ground contact detection signal of the first ground

contact sensor of each leg is a signal indicating contact
with the ground and if a ground contact detection signal
of the second ground contact sensor of the leg is a signal
indicating no contact with the ground, then the horizontal

5   position of the ankle joint of the leg is estimated as the
horizontal position of a floor reaction force acting point
of the leg, or if a ground contact detection signal of the
first ground contact sensor of each leg is a signal
indicating no contact with the ground and if a ground

10   contact detection signal of the second ground contact
sensor of the leg is a signal indicating contact with the
ground, then the horizontal position of the
metatarsophalangeal joint of the leg is estimated as the
horizontal position of a floor reaction force acting point

15   of the leg, or if ground contact detection signals of both
the first ground contact sensor and the second ground
contact sensor of each leg are signals indicating contact
with the ground and if the position of the center of
gravity is behind the position of the ankle joint of the

20   leg in the advancing direction of the biped walking mobile
body, then the horizontal position of the ankle joint of
the leg is estimated as the horizontal position of a floor
reaction force acting point of the leg, or if ground
contact detection signals of both the first ground contact

25   sensor and the second ground contact sensor of each leg
are signals indicating contact with the ground and if the
position of the center of gravity is before the position

of the metatarsophalangeal joint of the leg in the

advancing direction of the biped walking mobile body, then

the horizontal position of the metatarsophalangeal joint

of the leg is estimated as the horizontal position of a

5   floor reaction force acting point of the leg, or if ground

contact detection signals of both the first ground contact

sensor and the second ground contact sensor of each leg

are signals indicating contact with the ground and if the

position of the center of gravity is between the position

10   of the ankle joint of the leg and the position of the

metatarsophalangeal joint in the advancing direction of

the biped walking mobile body, then the horizontal

position of the center of gravity is estimated as the

horizontal position of a floor reaction force acting point

15   of the leg.

With this arrangement, the accuracy of estimating

the horizontal position of a floor reaction force acting

point can be enhanced independently of the motion mode or

the like of the biped walking mobile body.

20   Further, according to the method of estimating a

floor reaction force acting point in accordance with the

present invention, regarding the estimation of the

vertical position of a floor reaction force acting point,

the vertical distance from the ankle joint to a ground

25   contact surface of each leg when the biped walking mobile

body is in, for example, an upright stationary state, is

measured and retained in a memory beforehand, and when the

vertical distance from the ankle joint to the ground
contact surface of each leg in contact with the ground is
grasped in the first step, the vertical distance retained
in the memory is grasped as the vertical distance from the

5   ankle joint to the ground contact surface of each leg in
contact with the ground. The upright stationary state of
the biped walking mobile body more technically means a
state wherein the biped walking mobile body is standing
with both legs thereof and its body stretched

10   substantially in the vertical direction and with
substantially entire surfaces of the soles of the feet of
both legs in contact with the ground.

        More specifically, according to the knowledge of
the inventors of the present application, the vertical

15   distance from the ankle joint to the ground contact
surface of the leg in contact with the ground generally
does not change much while the biped walking mobile body
is in a motion, such as walking on a level ground, and
will be approximately almost equal to the vertical

20   distance from the ankle joint to the ground contact
surface of each leg while the biped walking mobile body is
in the upright stationary state. Hence, the vertical
position of a floor reaction force acting point can be
easily estimated by measuring and retaining in a memory

25   beforehand the vertical distance from the ankle joint to
the ground contact surface of each leg in the upright
stationary state, and by grasping the vertical distance

retained in the memory as the vertical distance from the ankle joint to the ground contact surface of the leg in contact with the ground while the biped walking mobile body is in motion.

5   To estimate the vertical position of a floor reaction force acting point with even higher accuracy, preferably, the vertical distance from the ankle joint to the ground contact surface of each leg and the vertical distance from the metatarsophalangeal joint to the ground

10   contact surface of the leg while the biped walking mobile body is in the upright stationary state are measured and retained in a memory beforehand as a first basic vertical distance and a second basic vertical distance, respectively, and when the vertical distance from the

15   ankle joint to the ground contact surface of each leg in contact with the ground is grasped in the first step, if the position of the center of gravity is behind the position of the metatarsophalangeal joint of the leg in the advancing direction of the biped walking mobile body,

20   then the first basic vertical distance is grasped as the vertical distance from the ankle joint to the ground contact surface of the leg, or if the position of the center of gravity is before the position of the metatarsophalangeal joint in the advancing direction of

25   the biped walking mobile body, then the vertical distance between the ankle joint and the metatarsophalangeal joint of the leg is determined and then the value obtained by

adding the second basic vertical distance to the
determined vertical distance is grasped as the vertical
distance from the ankle joint to the ground contact
surface of the leg.

5   More specifically, if the position of the center of
gravity is behind the position of the metatarsophalangeal
joint of a leg in the advancing direction of the biped
walking mobile body, then at least bottom surface of the
heel of the foot of the leg is in contact with the ground,
10   so that the vertical distance from the ankle joint to the
ground contact surface of the leg in contact with the
ground while the biped walking mobile body is in motion is
substantially equal to the first basic vertical distance.
Further, if the position of the center of gravity is
15   before the position of the metatarsophalangeal joint of
the leg in the advancing direction of the biped walking
mobile body, then the foot of the leg is normally in
contact with the ground at a place adjacent to its toe (a
place near the metatarsophalangeal joint), whereas its
20   heel is floating. In this case, the vertical distance
from a foot joint of the leg to the ground contact surface
is substantially equal to the value obtained by adding the
second basic vertical distance to the vertical distance
between the foot joint and the metatarsophalangeal joint.
25   In this case, the vertical distance between the foot joint
and the metatarsophalangeal joint can be determined from
the positions of those joints grasped in the first step.

Thus, by grasping the vertical distance from the ankle joint to the ground contact surface of a leg according as whether the position of the center of gravity is behind or before the position of the

5   metatarsophalangeal joint in the advancing direction of the biped walking mobile body, as described above, the accuracy of the vertical distance can be enhanced. As a result, the accuracy of an estimated value of the vertical position of a floor reaction force acting point can be

10   further enhanced.

Next, a method of estimating a joint moment of a biped walking mobile body in accordance with the present invention is a method of estimating a moment acting on at least one joint of each leg of a biped walking mobile body

15   by using an estimated value of the position of a floor reaction force acting point successively determined by the floor reaction force estimating method according to the present invention described above. And this joint moment estimating method includes a step for successively

20   estimating the floor reaction force of each leg, which is in contact with the ground, of the biped walking mobile body by using at least a detection output of an acceleration sensor attached to a body of the biped walking mobile body to detect the acceleration of a

25   predetermined part of the body of the biped walking mobile body and a detection output of a body inclination sensor attached to the body to detect an inclination angle of the

body, and a step for successively grasping the inclination angle of each rigid corresponding part of a biped walking mobile body that corresponds to each rigid body of a rigid link model representing the biped walking mobile body in the form of a link assembly of a plurality of rigid bodies, the acceleration of the center of gravity of the rigid corresponding part, and the angular acceleration of the rigid corresponding part by using at least detection outputs of the body inclination sensor and an angle sensor attached to a joint to detect the bending angle of a joint of each leg of the biped walking mobile body, wherein the moment acting on at least one joint of each leg of the biped walking mobile body is estimated on the basis of an inverse dynamics model by using an estimated value of the floor reaction force, an estimated value of the position of the floor reaction force acting point, an inclination angle of the aforesaid each rigid corresponding part, an acceleration of the center of gravity of the rigid corresponding part and an angular acceleration of the rigid corresponding part, the weight and size of each rigid corresponding part determined in advance, the position of the center of gravity of each rigid corresponding part in the rigid corresponding part determined in advance, and an inertial moment of each rigid corresponding part determined in advance.

According to the joint moment estimating method in accordance with the present invention, although it will be

discussed in detail later, successively detecting the
acceleration of a predetermined part (e.g., the waist) of
a body (torso) of a biped walking mobile body by an
acceleration sensor and also successively detecting the
5   inclination angle of the body by a body inclination sensor
allow the floor reaction force acting on each leg in
contact with the ground to be successively estimated by
using the detection outputs (detected values). Further,
successively detecting the bending angle of a joint of
10   each leg by an angle sensor in addition to detecting the
inclination angle of the body by a body inclination sensor
makes it possible to successively grasp the inclination
angle (this indicates the mutual posture relationship
among rigid corresponding parts) of each rigid
15   corresponding part (thigh, crus, etc.) of a rigid link
model representing a biped walking mobile body, the
acceleration of the center of gravity of the rigid
corresponding part, and the angular acceleration of the
rigid corresponding part by using the detection outputs
20   (detected values) of the aforesaid body inclination sensor
and the angle sensor. This means that the mutual posture
relationship among rigid corresponding parts will be known
if the inclination angle of the body and the bending
angles of joints of each leg are known, so that the
25   inclination angles of the rigid corresponding parts will
be known. Further, the position of the center of gravity
of a rigid corresponding part in the rigid corresponding

part (the position of the center of gravity of the rigid

corresponding part in a coordinate system fixed to each

rigid corresponding part) can be determined in advance;

therefore, based on this and the mutual posture

5 relationship among the rigid corresponding parts, the

position of the center of gravity of each rigid

corresponding part (the position relative to a reference

point fixed at an arbitrary position (e.g., the waist) of

a biped walking mobile body) in the entire biped walking

10 mobile body (in the entire rigid link model) can be known.

And, the acceleration of the center of gravity can be

grasped as the second-order differentiation value of the

position of the center of gravity of each rigid

corresponding part. Further, if the inclination angle of

15 each rigid corresponding part is known, then the angular

acceleration of each rigid corresponding part can be

grasped as the second-order differentiation value thereof.

Further, when the floor reaction force of a biped

walking mobile body has been estimated, and the

20 inclination angle of each rigid corresponding part, the

acceleration of the center of gravity of the rigid

corresponding part, and the angular acceleration of the

rigid corresponding part have been grasped, as described

above, these pieces of data and the estimated value of a

25 floor reaction force acting point determined by the

aforesaid floor reaction force acting point estimating

method, the weight and size (especially length) of each

rigid corresponding part determined in advance, the
position of the center of gravity of each rigid
corresponding part in the rigid corresponding part
determined in advance, and the inertial moment of each
5   rigid corresponding part determined in advance can be used
to estimate the moment acting on a knee joint or a hip
joint of each leg on the basis of a publicly known so-
called inverse dynamics model. Briefly speaking, the
technique based on the inverse dynamics model uses an
10   equation of motion related to the translational motion of
the center of gravity of each rigid corresponding part of
a biped walking mobile body and an equation of motion
related to a rotational motion of the rigid corresponding
part (e.g., the rotational motion about the center of
15   gravity of the rigid corresponding part) to determine the
moments acting on joints of the biped walking mobile body
that correspond to the joints of a rigid link model in
order from the one closest to a floor reaction force
acting point. Although it will be discussed in detail
20   later, if it is assumed that, for example, each leg is a
link assembly having a thigh and a crus as rigid
corresponding parts, then the force acting on the knee
joint of the leg (the joint reaction force) will be known
by applying the acceleration of the center of gravity of
25   the crus, an estimated value of the floor reaction force
acting on the leg, and a value of the weight of the crus
to the equation of motion related to the translational

motion of the center of gravity of the crus of each leg.
Furthermore, the moment of the knee joint of the leg can
be estimated by applying a joint reaction force acting on
the knee joint of the leg, an angular acceleration of the
5   crus of the leg, an estimated position of the floor
reaction force acting point of the leg, an estimated value
of the floor reaction force of the leg, the position of
the center of gravity of the crus in the crus, a data
value related to the size (length) of the crus, a value of
10   the inertial moment of the crus, and a value of the
inclination angle of the crus to an equation of motion
related to a rotational motion of the crus.

In addition, the joint reaction force acting on the
hip joint of the leg can be determined by applying an
15   acceleration of the center of gravity of the thigh, a
joint reaction force acting on the knee joint of the leg,
and a value of the weight of the thigh to an equation of
motion related to the translational motion of the center
of gravity of the thigh of each leg. Further, the moment
20   of the hip joint of the leg can be estimated by applying
joint reaction forces acting on the knee joint and the hip
joint, respectively, of the leg, an angular acceleration
of the thigh of the leg, a position of the center of
gravity of the thigh in the thigh and a data value related
25   to the size (length) of the thigh, a value of the inertial
moment of the thigh, and a value of the inclination angle
of the thigh to an equation of motion related to the

rotational motion of the thigh.

The joint moment estimating method in accordance with the present invention makes it possible to estimate, in real time, the moment acting on a joint of a leg by

5   relatively simple arithmetic processing by using the floor reaction force acting point estimated according to the floor reaction force acting point estimating method in accordance with the present invention described above so as to estimate the moment acting on a joint of a leg, thus

10   obviating the need for preparing multiple types of correlation data beforehand or for attaching a relatively large sensor or the like to a biped walking mobile body.

Brief Description of the Drawings

15   Figs. 1 (a) and (b) are diagrams for explaining a basic principle of a method of estimating floor reaction forces in an embodiment of the present invention, Fig. 2 is a diagram schematically showing a human being as a bipedal walking mobile body and a construction of an

20   apparatus installed on the human being in an embodiment of the present invention, Fig. 3 is a block diagram for explaining the functions of an arithmetic processing unit installed in the apparatus shown in Fig. 2, and Fig. 4 is a diagram showing a rigid link model used for processing

25   of the arithmetic processing unit shown in Fig. 3. Fig. 5 is a diagram for explaining a technique for calculating the position (horizontal position) of a

metatarsophalangeal joint in a first embodiment of the
present invention and a technique for grasping the
distance from an ankle joint to a ground contact surface,
Figs. 6 (a) and (b) and Figs. 7 (a) to (c) are diagrams
for explaining a technique for estimating the horizontal
positions of floor reaction force acting points, and Fig.
8 is a diagram for explaining the processing in a joint
moment estimating means of the arithmetic processing unit
of Fig. 3. Fig. 9 and Fig. 10 are graphs illustrating the
time-dependent changes in the horizontal position and the
vertical position, respectively, of a floor reaction force
acting point in a level-ground walking mode determined
according to the first embodiment of the present invention,
Fig. 11 and Fig. 12 are graphs illustrating the time-
dependent changes in a knee joint moment and a hip joint
moment, respectively, in the level-ground walking mode
determined according to the first embodiment of the
present invention, Fig. 13 and Fig. 14 are graphs
illustrating the time-dependent changes in a knee joint
moment and a hip joint moment, respectively, in a
staircase descent walking mode determined according to the
first embodiment of the present invention, Fig. 15 and Fig.
16 are graphs illustrating the time-dependent changes in a
knee joint moment and a hip joint moment, respectively, in
a staircase ascent walking mode determined according to
the first embodiment of the present invention, Fig. 17 and
Fig. 18 are graphs illustrating the time-dependent changes

in a knee joint moment and a hip joint moment,
respectively, in a sitting-onto-a-chair mode determined
according to the first embodiment of the present invention,
and Fig. 19 and Fig. 20 are graphs illustrating the time-
dependent changes in a knee joint moment and a hip joint
moment, respectively, in a rising-from-a-chair mode
determined according to the first embodiment of the
present invention. Fig. 21 is a diagram for explaining a
technique for calculating the position of a
metatarsophalangeal joint in a second embodiment of the
present invention and a technique for grasping the
distance from an ankle joint to a ground contact surface.

Best Mode for Carrying Out the Invention

An embodiment to which a method of estimating a
floor reaction force acting point and a method of
estimating a joint moment in accordance with the present
invention will be explained with reference to the
accompanying drawings. First, for the convenience of
understanding, the basic concept of the technique for
estimating floor reaction forces of a biped walking mobile
body in the embodiment of the present invention will be
explained with reference to Fig. 1. The motional state of
a leg of a biped walking mobile body, e.g., the motional
state of a leg in a walking mode, comes in a single stance
state in which only one leg 2 (the front leg, as observed
in the advancing direction of a biped walking mobile body

1 in the figure) of both legs 2 and 2 of the biped walking
mobile body 1 is in contact with the ground, as shown in
Fig. 1(a), and a double stance state in which both legs 2
and 2 are in contact with the ground, as shown in Fig.

5   1(b).

Here, first, in the single stance state, the equation
of motion (to be more specific, an equation of motion
related to the translational motion of a center of
gravity) of the center of gravity of the biped walking

10   mobile body 1 in an absolute coordinate system fixed to
the floor on which the biped walking mobile body 1 moves
provides a relational expression in which the product of
the acceleration of the center of gravity and the weight
of the biped walking mobile body 1 is equal to the

15   resultant force of the gravity acting on the center of
gravity (= weight of the biped walking mobile body 1 x
acceleration of gravity) and the floor reaction force
acting from the floor to the ground contact portion of the
leg 2 in contact with the ground. Specifically, as shown

20   in, for example, Fig. 1 (a), if the components of an
acceleration a (vector) of a center of gravity G0 of the
biped walking mobile body 1 in an X-axis direction (the
horizontal direction relative to the advancing direction
of the biped walking mobile body 1) and in a Z-axis

25   direction (the vertical direction) are denoted by ax and
az, respectively, and the components of a floor reaction
force F (vector) related to the leg 2 in contact with the

ground (the supporting leg 2) in the X-axis direction and the Z-axis direction are denoted by Fx and Fz, respectively, in an absolute coordinate system Cf fixed to a floor A, then the equation of motion of the center of gravity G0 is represented by Equation (1) given below.

$$^T(Fx, Fz - M \cdot g) = M \cdot {}^T(ax, az) \quad \ldots \ldots (1)$$

(where M: Weight of the biped walking mobile body, g: Acceleration of gravity)

The parenthesized portions $^T(\ ,\ )$ on both sides in Equation (1) mean the vectors of two components. In the present description, the notation of $^T(\ ,\ )$ will denote a vector.

Thus, if the acceleration $a = {}^T(ax, az)$ of the center of gravity G0 of the biped walking mobile body 1 is grasped, then the estimated value of the floor reaction force $F = {}^T(Fx, Fz)$ can be obtained according to the following Equation (2) by using the acceleration a, the value of the weight M of the biped walking mobile body 1, and the value of the acceleration of gravity g.

$$^T(Fx, Fz) = M \cdot {}^T(ax, az - g) \quad \ldots \ldots (2)$$

In this case, the weight M necessary to obtain the estimated value of the floor reaction force F can be grasped beforehand by measurement or the like. Although it will be discussed in detail hereinafter, the position and the acceleration a of the center of gravity G0 can be successively grasped by a publicly known technique or the like by using outputs of sensors, such as a sensor for

detecting bending angles (rotational angles) of joints of the biped walking mobile body 1, an acceleration sensor, and a gyro sensor.

An equation of motion of the center of gravity of the biped walking mobile body 1 (specifically, an equation of motion related to the translational motion of the center of gravity) in the state wherein both legs are in contact with the ground provides a relational expression in which the product of the acceleration of the center of gravity and the weight of the biped walking mobile body 1 is equal to the resultant force of the gravity acting on the center of gravity (= weight of the biped walking mobile body x acceleration of gravity) and the floor reaction forces acting from the floor to the ground contact portion of each of the two legs 2 and 2 (two floor reaction forces associated with the two legs 2 and 2, respectively). Specifically, as shown in, for example, Fig. 1 (b), if the XZ coordinate components of a floor reaction force Ff related to the leg 2 at the front side with respect to the advancing direction of the biped walking mobile body 1 are denoted by Ffx and Ffz, and the XZ coordinate components of a floor reaction force Fr related to the leg 2 at the rear side are denoted by Frx and Frz, then the equation of motion of the center of gravity G0 is represented by Equation (3) given below.

$$^{T}(Ffx + Frx, Ffz + Frz - M \cdot g) = M \cdot {}^{T}(ax, az)$$

$$\cdots \cdots (3)$$

The meanings of ax, az, M, and g in Equation (3) are as described above.

Meanwhile, according to the knowledge of the inventors of the present application, the floor reaction forces Ff and Fr related to the legs 2 and 2, respectively, in the double stance state may be considered to generally act toward the center of gravity G0 of the biped walking mobile body 1 from particular parts in the vicinity of the bottom ends of the legs 2 and 2, e.g., the portions of ankle joints 12f and 12r, as shown in Fig. 1 (b). And, at this time, a certain relational expression holds between the positions of the ankle joints 12f and 12r of the legs 2 and 2 relative to the center of gravity G0 and the floor reaction forces Ff and Fr acting on the legs 2 and 2, that is, a relational expression representing a relationship in which the direction of a segment connecting the center of gravity G0 and the ankle joints 12f and 12r of the legs 2 and 2 (the direction of the positional vectors of the ankle joints 12f and 12r relative to the center of gravity G0) agrees with the direction of the floor reaction forces Ff and Fr related to the legs 2 and 2.

Specifically, referring to Fig. 1 (b), if the coordinates of the position of the center of gravity G0 in the absolute coordinate system Cf is denoted by (Xg, Zg), the coordinates of the position of the ankle joint 12f of the leg 2 at the front side is denoted by (Xf, Zf), and the coordinates of the position of the ankle joint 12r of

the leg 2 at the rear side is denoted by (Xr, Zr), then the above relational expression will be the following equation (4):

$$(Zf-Zg)/(Xf-Xg)=Ffz/Ffx$$

5
$$(Zr-Zg)/(Xr-Xg)=Frz/Frx$$

$$\dots \dots (4)$$

Equation (5) given below is derived from the Equation (4) and the above Equation (3):

$$Ffx = M \cdot \{\Delta Xf \cdot (\Delta Zr \cdot ax - \Delta Xr \cdot az$$

10
$$- \Delta Xr \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf)$$

$$Ffz = M \cdot \{\Delta Zf \cdot (\Delta Zr \cdot ax - \Delta Xr \cdot az$$

$$- \Delta Xr \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf)$$

$$Frx = M \cdot \{\Delta Xr \cdot (-\Delta Zf \cdot ax + \Delta Xf \cdot az$$

$$+ \Delta Xf \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf)$$

15
$$Frz = M \cdot \{\Delta Zr \cdot (-\Delta Zf \cdot ax + \Delta Xf \cdot az$$

$$+ \Delta Xf \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf)$$

$$\dots \dots (5)$$

(where $\Delta Xf=Xf-Xg$, $\Delta Zf=Zf-Zg$,

$\Delta Xr=Xr-Xg$, $\Delta Zr=Zr-Zg$)

20   Accordingly, if the acceleration $a = {}^T(ax, az)$ of the center of gravity G0 of the biped walking mobile body 1 is grasped and the positions of the ankle joints 12f, 12r of the legs 2, 2 relative to the center of gravity G0 of the biped walking mobile body 1 (these are denoted by ΔXf, ΔZf,

25   ΔXr, and ΔZr in Equation (5)) are grasped, then the estimated values of the floor reaction forces $Ff = {}^T(Ffx, Ffz)$ and $Fr = {}^T(Frx, Frz)$ of each leg 2 can be obtained

according to the above Equation (5) by using the
acceleration a, the positions of the ankle joints 12f, 12r,
the value of the weight M of the biped walking mobile body
1, and the value of the acceleration of gravity g.

5   In this case, the weight M necessary to obtain the
estimated values of the floor reaction forces Ff and Fr
can be grasped beforehand by measurement or the like.
Although it will be discussed in detail hereinafter, the
acceleration a of the center of gravity G0, the position

10   of the center of gravity G0, and the positions of the
ankle joints 12f, 12r relative to the center of gravity G0
can be successively grasped by a publicly known technique
or the like by using outputs of sensors, such as a sensor
for detecting bending angles (rotational angles) of joints

15   of the biped walking mobile body 1, an acceleration sensor,
and a gyro sensor.

The embodiments (first and second embodiments)
explained below are adapted to estimate the floor reaction
force acting point and joint moments of each leg 2 while

20   estimating the floor reaction force of each leg 2 at the
same time on the basis of the matters explained above.

The first embodiment in which the present invention
has been applied to a human being as a biped walking
mobile body will now be explained in detail.

25   As schematically shown in Fig. 2, a human being 1
is roughly constructed of a pair of right and left legs 2,
2, a torso 5 composed of a waist 3 and a chest 4, a head 6,

and a pair of right and left arms 7, 7. In the torso 5, the waist 3 is connected to the legs 2, 2 through the intermediary of a pair of right and left hip joints 8, 8, and is supported on the two legs 2, 2. The chest 4 of the torso 5 exists on the upper side of the waist 3 such that it can be tilted toward the front of the human being 1 with respect to the waist 3. And, the arms 7, 7 are provided such that they extend from right and left sides of the upper part of the chest 4, and the head 6 is supported on the upper end of the chest 4.

Each of the legs 2 and 2 has a thigh 9 extending from the hip joint 8 and a crus 11 extending from the distal end of the thigh 9 through the intermediary of a knee joint 10, a foot 13 being connected to the distal end of the crus 11 through the intermediary of an ankle joint 12.

In the present embodiment, an apparatus described below is attached to the human being 1 to estimate a floor reaction force acting on each leg 2 of the human being 1 that has such a construction, and the acting point thereof, and also to estimate the moments acting on the knee joints 10 and the hip joints 8.

More specifically, attached to the chest 4 of the torso 5 are a gyro sensor 14 that generates outputs based on angular velocities involved in inclinations of the chest 4 (hereinafter referred to as "the chest gyro sensor 14"), an acceleration sensor 15 that generates outputs

based on longitudinal accelerations of the chest 4

(hereinafter referred to as "the chest longitudinal

acceleration sensor 15"), an arithmetic processing unit 16

constructed of a CPU, a RAM, a ROM, etc., and a battery 17

5   that provides a power supply of the arithmetic processing

unit 16, etc. In this case, these chest gyro sensor 14,

the chest longitudinal acceleration sensor 15, the

arithmetic processing unit 16, and the battery 17 are

accommodated in a shoulder-bag type housing member 18

10   secured to, for example, the chest 4, through a belt or

the like, which is not shown, and are integrally secured

to the chest 4 through the intermediary of the housing

member 18.

　　　More technically, the acceleration indicated by an

15   output of the chest longitudinal acceleration sensor 15 is

the longitudinal acceleration in the direction of a

horizontal section of the chest 4 (the direction

orthogonal to the axis of the chest 4), and it is the

acceleration in the longitudinal horizontal direction (in

20   the direction of the X-axis of the absolute coordinate

system Cf of Fig. 2) in a state wherein the human being 1

is standing upright on a level ground, while in a state

wherein the waist 3 or the chest 4 is inclined from the

vertical direction (the direction of the Z-axis of the

25   absolute coordinate system Cf of Fig. 2), it is the

acceleration in the direction inclined relative to the

horizontal direction by an inclination angle relative to

the vertical direction of the chest 4.

Further, a gyro sensor 19 that generates outputs based on angular velocities involved in inclinations of the waist 3 (hereinafter referred to as "the waist gyro sensor 19"), an acceleration sensor 20 that generates outputs based on longitudinal accelerations of the waist 3 (hereinafter referred to as "the waist longitudinal acceleration sensor 20"), and an acceleration sensor 21 that generates outputs based on vertical accelerations of the waist 3 (hereinafter referred to as "the waist vertical acceleration sensor 21") are integrally mounted and secured to the waist 3 of the torso 5 through the intermediary of a securing means, such as a belt, which is not shown.

More technically, the waist longitudinal acceleration sensor 20 is a sensor that detects the longitudinal accelerations in the direction of a horizontal section of the waist 3 (the direction orthogonal to the axis of the waist 3), as in the case of the chest longitudinal acceleration sensor 15. More technically, the waist vertical acceleration sensor 21 is a sensor that detects vertical accelerations in the axial direction of the waist 3 (this is orthogonal to the accelerations detected by the waist longitudinal acceleration sensor 20). The waist longitudinal acceleration sensor 20 and the waist vertical acceleration sensor 21 may be integrally constructed by a biaxial acceleration sensor.

Further, attached to the hip joint 8 and the knee
joint 10 of each leg 2 are a hip joint angle sensor 22 and
a knee joint angle sensor 23 that generate outputs based
on bending angles $\Delta\theta c$ and $\Delta\theta d$, respectively, thereof.

5   Regarding the hip joint angle sensor 22, Fig. 2 shows only
the hip joint angle sensor 22 related to the hip joint 8
of the leg 2 on the front side (on the right side, as
observed in the forward direction from the human being 1);
however, another hip joint angle sensor 22 is attached

10   concentrically with the hip joint angle sensor 22 on the
front side to the hip joint 8 of the leg 2 on the other
side (on the left side, as observed in the forward
direction from the human being 1).

These angle sensors 22 and 23 are composed of, for

15   example, potentiometers, and mounted on each leg 2 through
the intermediary of a means, such as a band member, which
is not shown. Here, in the example of the present
embodiment, the bending angle $\Delta\theta c$ detected by each hip
joint angle sensor 22 is, more technically, the rotational

20   angle about the hip joint 8 of the thigh 9 of each leg 2
with respect to the waist 3 (about the axis of the hip
joint 8 in the lateral direction of the human being 1),
this being based on when the posture relationship between
the waist 3 and the thigh 9 of each leg 2 indicates a

25   predetermined posture relationship (e.g., the posture
relationship in which the axis of the waist 3 and the axis
of the thigh 9 are substantially parallel, as in the state

wherein the human being 1 is upright and stationary).
Similarly, the bending angle $\Delta\theta d$ detected by each knee
joint angle sensor 23 is the rotational angle about the
knee joint 10 of the crus 11 relative to the thigh 9
5   (about the axis of the knee joint 10 in the lateral
direction of the human being 1), this being based on when
the posture relationship between the thigh 9 and the crus
11 of each leg 2 indicates a predetermined posture
relationship (e.g., the posture relationship in which the
10   axis of the thigh 9 and the axis of the crus 11 are
substantially parallel). The axis of the thigh 9 is a
straight line connecting the center of the joint (hip
joint 8) at one end of the thigh 9 and the center of the
joint (knee joint 10) at the other end thereof. Similarly,
15   the axis of the crus 11 is a straight line connecting the
centers of the joints (the knee joint 10 and the ankle
joint 12) at both ends thereof.

Furthermore, at two places on the bottom surface of
the foot 13 of each leg 2, ground contact sensors 51f and
20   51r for detecting contact or no contact of the places with
the ground are installed. More specifically, the ground
contact sensors 51f and 51r are attached to the shoe sole
of each foot 13, the shoe being worn by the human being 1.
In this case, the ground contact sensors 51f and 51r of
25   each foot 13 are provided longitudinally apart from each
other at a place directly below the metatarsophalangeal
joint 13a (indicated by a dark dot in Fig. 2, hereinafter

being referred to as "the MP joint 13a") of the foot 13
and a place directly below the ankle joint 12,
respectively, and they output ON/OFF signals on the basis
of contact or no contact of the respective places with the
5   ground. More technically, the MP joint 13a is the joint
of the thumb root of the foot 13. The place directly
below the MP joint 13a means, more precisely, a place
vertically below the MP joint 13a in a state wherein the
human being 1 is in a substantially upright posture
10   (upright stationary state) with substantially the entire
bottom surface of the foot 13 in contact with a flat floor
surface. The same applies to the place directly below the
ankle joint 12. In the following explanation, the ground
contact sensor 51f may be referred to as the directly
15   below MP ground contact sensor 51f, and the ground contact
sensor 51r, as the directly below ankle ground contact
sensor 51r.

The aforesaid sensors 14, 15, 19 to 23, 51f, and
51r are connected to the arithmetic processing unit 16
20   through signal lines, which are not shown, to input their
outputs to the arithmetic processing unit 16. In
association with the method of estimating floor reaction
force acting points in accordance with the present
invention, the directly below MP ground contact sensor 51f
25   and the directly below ankle ground contact sensor 51r
correspond to the second ground contact sensor and the
first ground contact sensor, respectively. Further, in

association with the joint moment estimating method in
accordance with the present invention, the sensors 14, 15,
19 and 20 mean body inclination sensors for detecting the
inclination angles of the body of the human being 1 as a

5   biped walking mobile body, and the sensors 20 and 21 mean
sensors for detecting the accelerations of the waist 3 as
a particular part of the human being 1 (the biped walking
mobile body).

In Fig. 2, the components marked with parenthesized

10   reference numerals 24 are ankle joint angle sensors that
output signals based on the bending angles of the ankle
joint 12 of each leg 2, and are related to the second
embodiment, which will be discussed later. In the present
embodiment (the first embodiment), the ankle joint angle

15   sensors 24 are unnecessary and not actually provided.

The arithmetic processing unit 16 is equipped with
the functional means shown in Fig. 3. In Fig. 3, the
parenthesized portion (the portion of the ankle joint
angle sensor 24) and the portion indicated by the chain

20   double-dashed line are related to the second embodiment to
be discussed later, and these parenthesized portion and
the portion indicated by the chain double-dashed line are
unnecessary. Therefore, in the following explanation of
the arithmetic processing unit 16 in the present

25   embodiment, nothing related to these parenthesized portion
and the portion enclosed by the chain double-dashed line
will be referred to.

As shown in Fig. 3, the arithmetic processing unit 16 in the present embodiment is equipped with a leg motion determining means 25 that uses the detection data of the ground contact sensors 51r and 51f so as to determine

5   whether the motion states of the legs 2, 2 of the human being 1 are in the single stance state (the state shown in Fig. 1 (a)) or the double stance state (the state shown in Fig. 1 (b)). The arithmetic processing unit 16 is further provided with a chest inclination angle measuring means 26

10   that uses the detection data of the chest longitudinal acceleration sensor 15 and the chest gyro sensor 14 thereby to measure an inclination angle θa in an absolute coordinate system Cf of the chest 4 (specifically, the inclination angle θa with respect to a vertical direction:

15   refer to Fig. 2) and a waist inclination angle measuring means 27 that uses the detection data of the waist longitudinal acceleration sensor 20 and the waist gyro sensor 19 so as to measure an inclination angle θb in an absolute coordinate system Cf of the waist 3 (specifically,

20   the inclination angle θb relative to a vertical direction: refer to Fig. 2).

The arithmetic processing unit 16 is further provided with a reference acceleration measuring means 28 that uses the detection data of the waist longitudinal

25   acceleration sensor 20 and the waist vertical acceleration sensor 21 and the data of the inclination angle θb of the waist 3 measured by the waist inclination angle measuring

means 27 so as to determine an acceleration (translational acceleration) $a_0={}^T(a_0x, a_0z)$ in the absolute coordinate system Cf at an origin O of a bodily coordinate system Cp (the xz-coordinate system in Fig. 2) set at the waist 3,

5   as shown in Fig. 2, as the reference point of the human being 1 in the present embodiment. Here, the bodily coordinate system Cp is, to be more specific, a coordinate system, for example, that has a midpoint of a line connecting centers of the right and left hip joints 8, 8,

10   respectively, of the human being 1 defined as the origin O, a vertical direction being defined as a z-axis direction, and a forward horizontal direction of the human being 1 defined as an x-axis direction. The directions of the three axes are the same as those in the aforesaid absolute

15   coordinate system Cf.

The arithmetic processing unit 16 is further provided with a leg posture calculating means 29 that uses detection data of the hip joint angle sensor 22 and the knee joint angle sensor 23 of each leg 2 and the data of

20   the inclination angle θb of the waist 3 obtained by the waist inclination angle measuring means 27 thereby to determine inclination angles θc and θd of the thigh 9 and the crus 11, respectively, of each leg 2 in an absolute coordinate system Cf (specifically, inclination angles θc

25   and θd relative to a vertical direction: refer to Fig. 2).

The arithmetic processing unit 16 is further provided with a means 30 for calculating the position of

the center of gravity of each portion by using data of an

inclination angle θa of the chest 4, an inclination angle

θb of the waist 3, and an inclination angle θc of the

thigh 9 and an inclination angle θd of the crus 11 of each

5 leg 2, which are obtained by the chest inclination angle

measuring means 26, the waist inclination angle measuring

means 27, and the leg posture calculating means 29, to

determine the position of the center of gravity of each

rigid corresponding part of the human being 1 associated

10 with a rigid link model to be discussed hereinafter

(specifically, the position of the center of gravity of

each rigid corresponding part in the bodily coordinate

system Cp), a bodily center of gravity position

calculating means 31 that uses the data of the position of

15 the center of gravity of the aforesaid rigid corresponding

part so as to determine the position of the center of

gravity of the entire human being 1 in the bodily

coordinate system Cp, an ankle position calculating means

32 that uses the data of the inclination angles θc and θd

20 of each of the thigh 9 and the crus 11 of each leg 2

obtained by the leg posture calculating means 29 so as to

determine the position of the ankle joint 12 of each leg 2

in the bodily coordinate system Cp, and further uses the

data of the position of the center of gravity G0 of the

25 entire human being 1 (refer to Fig. 1: hereinafter

referred to as "the bodily center of gravity G0") obtained

by the bodily center of gravity position calculating means

31 to determine the position of the ankle joint 12 of the

leg 2 relative to the bodily center of gravity G0

(specifically, ΔXf, ΔZf, ΔXr and ΔZr in the above Equation

(5)), an MP position calculating means 33 that uses the

5   data of the position of the ankle joint 12 (the position

in the bodily coordinate system Cp) obtained by the ankle

position calculating means 32 to determine the position

(specifically, the position in the x-axis direction) of an

MP joint 13a of the foot 13 of each leg 2 in the bodily

10   coordinate system Cp, and a bodily center of gravity

acceleration calculating means 34 that uses the data of

the position of the bodily center of gravity G0 obtained

by the bodily center of gravity position calculating means

31 and the data of the acceleration a_0 at the origin O of

15   the bodily coordinate system Cp obtained by the reference

acceleration measuring means 28 thereby to determine an

acceleration $a={}^T(ax, az)$(refer to Fig. 1) of the bodily

center of gravity G0 in the absolute coordinate system Cf.

     The arithmetic processing unit 16 is further

20   provided with a means 35 for calculating the acceleration

of each portion of a leg by using the data of the position

of the center of gravity of each rigid corresponding part

of the human being 1 (specifically, the position of the

center of gravity of a rigid corresponding part related to

25   the leg 2) obtained by the means 30 for calculating the

position of the center of gravity of each portion and the

data of the acceleration a_0 at the origin O of the bodily

coordinate system Cp obtained by the reference
acceleration measuring means 28 so as to determine the
acceleration (translational acceleration) of the center of
gravity of the thigh 9 and the crus 11 of each leg 2 in

5   the absolute coordinate system Cf, a means 36 for
calculating the angular acceleration of each portion of a
leg by using the data of the inclination angles θc and θd
of the thigh 9 and the crus 11 of each leg 2 obtained by
the leg posture calculating means 29 to determine the

10   angular accelerations of the thigh 9 and the crus 11 of
the legs 2, 2 in the absolute coordinate system Cf, and a
floor reaction force acting point estimating means 38 for
estimating the position of a floor reaction force acting
point of each leg 2 in contact with the ground on the

15   basis of the bodily center of gravity G0, the positions of
the ankle joint 12 and the MP joint 13a (the positions in
the bodily coordinate system Cp) determined by the bodily
center of gravity position calculating means 31, the ankle
position calculating means 32, and the MP position

20   calculating means 33, respectively, and detection outputs
of the ground contact sensors 51f and 51r of each leg 2.

The arithmetic processing unit 16 is further
provided with a floor reaction force estimating means 39
for determining the estimated value of a floor reaction

25   force acting on each leg 2 by using the data of the
acceleration a of the bodily center of gravity determined
by the bodily center of gravity acceleration calculating

means 34, the data of the position of the ankle joint 12
of each leg 2 relative to the bodily center of gravity G0
determined by the ankle position calculating means 32, and
the data of the determination result of the motion state
5 of the leg 2 given by the leg motion determining means 25,
and a joint moment estimating means 40 for estimating
moments acting on the knee joint 10 and the hip joint 8 of
each leg 2 by using this data of the estimated value of
the floor reaction force, the data of the accelerations of
10 the centers of gravity of the thigh 9 and the crus 11 of
each leg 2 obtained by the means 35 for calculating the
acceleration of each portion of a leg, the data of the
angular accelerations of the thigh 9 and the crus 11 of
each leg 2 obtained by the means 36 for calculating the
15 angular acceleration of each portion of a leg, the data of
the estimated position of a floor reaction force acting
point obtained by the floor reaction force acting point
estimating means 38, and the data of the inclination
angles θc and θd of the thigh 9 and the crus 11,
20 respectively, of each leg 2 obtained by the leg posture
calculating means 29.

An operation of the present embodiment will be
explained in combination with more detailed description of
the processing by each means of the aforementioned
25 arithmetic processing unit 16.

In the present embodiment, when, for example, the
human being 1 performs a motion of the legs 2, such as

walking, if a power switch, not shown, of the arithmetic

processing unit 16 is turned on while both legs 2 and 2

are in contact with a floor (while both feet 13 and 13 are

in contact with the ground), then processing is

5   successively carried out by the arithmetic processing unit

16 at a predetermined cycle time, as explained below,

thereby successively determining estimated values or the

like of floor reaction forces acting on each leg 2.

      More specifically, the arithmetic processing unit

10   16 first executes the processing of the leg motion

determining means 25. In the processing of the leg motion

determining means 25, ON/OFF of the ground contact sensors

51f and 51r of each leg 2 is determined for each cycle

time described above. And, if at least one of the ground

15   contact sensors 51f and 51r of one leg 2 outputs an ON

signal (the place of one of the ground contact sensors 51f

and 51r is in contact with the ground) and if at least one

of the ground contact sensors 51f and 51r of the other leg

2 outputs the ON signal, then it is determined that the

20   motion mode of the legs 2, 2 of the human being 1 is the

double stance state shown in Fig. 1 (b) mentioned above.

Further, if at least one of the ground contact sensors 51f

and 51r of one leg 2 outputs the ON signal and if none of

the ground contact sensors 51f and 51r of the other leg 2

25   output the ON signal (the places of both ground contact

sensors 51f and 51r are not in contact with the ground),

then it is determined that the motion mode of the legs 2,

2 of the human being 1 is the single stance state shown in Fig. 1 (a) mentioned above.

Whether it is the single stance state or the double stance state may be determined solely by the detection signals of the ground contact sensors 51f and 51r as described above. During a transition between the single stance state and the double stance state, the determination may be performed by considering also a change or the like in detection output of the waist vertical acceleration sensor 21.

In parallel to the processing of the leg motion determining means 25 as described above, the arithmetic processing unit 16 carries out the processing of the chest inclination angle measuring means 26 and the waist inclination angle measuring means 27. In this case, the processing by the chest inclination angle measuring means 26 successively determines the inclination angle θa of the chest 4 in the absolute coordinate system Cf at each cycle time mentioned above by a publicly known technique based on the so-called Kalman filter processing, using the detection data of the longitudinal accelerations of the chest 4 and the angular velocity of the chest 4 received from the chest longitudinal acceleration sensor 15 and the chest gyro sensor 14. Similarly, the processing by the waist inclination angle measuring means 27 successively determines the inclination angle θb of the waist 3 in the absolute coordinate system Cf by using the Kalman filter

processing from the detection data of the longitudinal accelerations of the waist 3 and the angular velocity of the waist 3 received from the waist longitudinal acceleration sensor 20 and the waist gyro sensor 19,

5 respectively. Here, the inclination angles θa and θb of the chest 4 and the waist 3, respectively, in the absolute coordinate system Cf denote inclination angles with respect to, for example, the vertical direction (gravitational direction) in the present embodiment.

10 The inclination angles of the chest 4 and the waist 3 can be alternatively determined by, for example, integrating the detection data of angular velocities obtained by the gyro sensors 14 and 19. However, performing the Kalman filter processing, as in the present

15 embodiment, allows the inclination angles θa and θb of the chest 4 and the waist 3 to be measured with high accuracy.

Next, the arithmetic processing unit 16 performs processing of the leg posture calculating means 29 and the processing of the reference acceleration measuring means

20 28.

In the processing implemented by the leg posture calculating means 29, the inclination angles θc and θd (inclination angles with respect to the vertical direction: refer to Fig. 2) of the thigh 9 and the crus 11

25 of each leg 2 are determined at each cycle time, as described below. The inclination angle θc of the thigh 9 of each leg 2 is calculated according to Equation (6)

given below on the basis of the current value of the

detection data of the bending angle $\Delta\theta c$ of the hip joint 8

obtained by the hip joint angle sensor 22 attached to the

leg 2 and the current value of the inclination angle θb of

5   the waist 3 determined by the waist inclination angle

measuring means 27:

$$\theta c = \theta b + \Delta\theta c \quad \dots \dots \quad (6)$$

where the inclination angle θb of the waist 3 takes

a negative value if the waist 3 inclines with respect to

10   the vertical direction such that an upper end portion of

the waist 3 juts out farther to the front side of the

human being 1 than a lower end portion thereof; and the

bending angle $\Delta\theta c$ of the hip joint 8 takes a positive

value if the thigh 9 inclines with respect to the axis of

15   the waist 3 such that a lower end portion of the thigh 9

juts out toward the front side of the human being 1.

Furthermore, the inclination angle θd of the crus

11 of each leg 2 is calculated according to Equation (7)

given below on the basis of the current value of the

20   inclination angle θc of the thigh 9 determined as

described above and the current value of the detection

data of the bending angle $\Delta\theta d$ of the knee joint 10

obtained by the knee joint angle sensor 23 attached to the

leg 2:

25   $$\theta d = \theta c - \Delta\theta d \quad \dots \dots \quad (7)$$

where the bending angle of the knee joint 10 takes

a positive value if the crus 11 inclines toward the rear

side of the thigh 9 with respect to the axis of the thigh 9.

In the processing of the reference acceleration measuring means 28, the acceleration $a_0={}^T(a_0x, a_0z)$ in the absolute coordinate system Cf of the origin O of the bodily coordinate system Cp is determined as described below. If the current value of the detection data of a longitudinal acceleration of the waist 3 obtained from the waist longitudinal acceleration sensor 20 is denoted by a_p, and the current value of the detection data of the vertical acceleration of the waist 3 obtained from the waist vertical acceleration sensor 21 is denoted by a_q, then the acceleration $a_0={}^T(a_0x, a_0z)$ in the absolute coordinate system Cf is determined according to Equation (8) given below from the detection data a_p and a_q and the current value of the inclination angle θb of the waist 3 obtained by the waist inclination angle measuring means 27:

$$a_0={}^T(a_0x, a_0z)$$
$$= {}^T(a_p \cdot \cos\theta b - a_q \cdot \sin\theta b, a_p \cdot \sin\theta b + a_q \cdot \cos\theta b-g)$$
$$\ldots \ldots (8)$$

The arithmetic processing unit 16 then carries out the processing of the means 30 for calculating the position of the center of gravity of each portion to determine the position of the center of gravity of each rigid corresponding part of the human being 1 in the bodily coordinate system Cp (the position relative to the

origin of the bodily coordinate system Cp), using a rigid link model explained below.

As shown in Fig. 4, a rigid link model R used in the present embodiment is a model representing the human being 1 by connecting rigid bodies R1, R1 corresponding to the thighs 9 of the respective legs 2, rigid bodies R2, R2 corresponding to the cruses 11, a rigid body R3 corresponding to the waist 3, and a rigid body R4 corresponding to a portion 38 combining the chest 4, the arms 7, 7, and the head 6 (hereinafter referred to as "the body 38"). In this case, the connection of the respective rigid bodies R1 and the rigid body R3 and the connection of the rigid bodies R1 and the rigid bodies R2 correspond to the hip joints 8 and the knee joints 10, respectively. In addition, the connection of the rigid body R3 and the rigid body R4 provides a tilt supporting point 39 of the chest 4 with respect to the waist 3.

In the present embodiment, the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts (the thighs 9 and the cruses 11 of the respective legs 2, the waist 3, and the body 38) of the human being 1 associated with the rigid bodies R1 to R4 of the rigid link model R in the rigid corresponding parts are determined beforehand and stored in a memory, not shown, of the arithmetic processing unit 16.

The positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts that have been

stored and retained in the arithmetic processing unit 16
are the positions in a coordinate system fixed with
respect to the rigid corresponding parts. In this case,
as examples of data indicating the positions of the

5   centers of gravity G1, G2, G3 and G4 of the rigid
corresponding parts, the distances in the axial direction
of the rigid corresponding parts from the midpoints of
joints at one end of each of the rigid corresponding parts
are used. Specifically, for example, the position of the

10 center of gravity G1 of each thigh 9 is indicated as the
position at a distance t1 in the axial direction of the
thigh 9 from the center of the hip joint 8 of the thigh 9,
and the position of the center of gravity G2 of each crus
11 is indicated as the position at a distance t2 in the

15 axial direction of the crus 11 from the center of the knee
joint 10 of the crus 11, as shown in Fig. 4. The values
of the distances t1 and t2 are determined beforehand and
retained in a memory in the arithmetic processing unit 16.
The same applies to the positions of the centers of

20 gravity G3 and G4 of other rigid corresponding parts.

Technically speaking, the position of the center of
gravity G4 of the body 38 is subject to influences of
motions of the arms 7 and 7 included in the body 38. In a
walking mode, the arms 7 and 7 are generally positionally

25 symmetrical with respect to the axis of the chest 4, so
that the position of the center of gravity G4 of the body
38 does not change much, and becomes substantially the

same as the position of the center of gravity G4 of the

body 38 in, for example, an upright stationary state.

According to the present embodiment, in addition to

the data indicating the positions of the centers of

5   gravity G1, G2, G3 and G4 of the rigid corresponding parts

(the thighs 9 and the cruses 11 of the legs 2, the waist 3,

and the body 38), the data of weights of the rigid

corresponding parts and the data of sizes of the rigid

corresponding parts (e.g., data of lengths of the rigid

10   corresponding parts) are determined beforehand and

retained in a memory in the arithmetic processing unit 16.

The weight of the crus 11 includes the weight of

the foot 13. As described above, the data to be stored

and retained in the arithmetic processing unit 16

15   beforehand may be determined by actual measurement or the

like, or may be estimated on the basis of human average

statistic data from height and weight of the human being 1.

Generally, the positions of the centers of gravity G1, G2,

G3 and G4, the weights and sizes of the rigid

20   corresponding parts are correlated with the height and

weight of a human being. Based on the correlation, from

the height and weight of the human being, the positions of

the centers of gravity G1, G2, G3 and G4, the weights, and

sizes of the rigid corresponding parts can be estimated

25   with relatively high accuracy.

The means 30 for calculating the position of the

center of gravity of each portion uses the data stored and

retained beforehand in the arithmetic processing unit 16,
as described above, the current values of the inclination
angle θa of the chest 4 (= the inclination angle of the
body 38) and the inclination angle θb of the waist 3

5   determined by the chest inclination angle measuring means
26 and the waist inclination angle measuring means 27,
respectively, and the current values of the inclination
angles θc and θd of the thigh 9 and the crus 11 of each
leg 2 determined by the leg posture calculating means 29

10   so as to determine the positions of the centers of gravity
G1, G2, G3 and G4 of the rigid corresponding parts in the
bodily coordinate system Cp (the xz-coordinate system
shown in Fig. 4) having the origin O fixed on the waist 3.

      In this case, the inclination angles θa to θd of

15   the rigid corresponding parts (the thighs 9 and the cruses
11 of the legs 2, the waist 3, and the body 38) have been
determined, as described above; therefore, the positions
and postures of the rigid corresponding parts in the
bodily coordinate system Cp are obtained from the data of

20   the inclination angles θa to θd and the data of the sizes
of the rigid corresponding parts. Thus, the positions of
the centers of gravity G1, G2, G3 and G4 of the rigid
corresponding parts in the bodily coordinate system Cp can
be determined.

25   Specifically, referring to, for example, Fig. 4,
regarding the leg 2 positioned on the left side in Fig. 4,
the inclination angle of the thigh 9 in the bodily

coordinate system Cp (the inclination angle relative to the z-axis direction) is θ_c (in this case, $\theta_c < 0$ in Fig. 4); hence, the coordinate of the position of the center of gravity G1 of the thigh 9 in the bodily coordinate system Cp is $(t_1 \cdot \sin\theta_c, -t_1 \cdot \cos\theta_c)$. The inclination angle in the bodily coordinate system Cp of the crus 11 is θ_d ($\theta_d < 0$ in Fig. 4); therefore, if the length of the thigh 9 is denoted by L_c, then the coordinate of the position of the center of gravity G2 of the crus 11 in the bodily coordinate system Cp will be $(L_c \cdot \sin\theta_c + t_2 \cdot \sin\theta_d, -L_c \cdot \cos\theta_c - t_2 \cdot \cos\theta_d)$. The centers of gravity of the thigh 9 and the crus 11 of the other leg 2, and of the waist 3 and the body 38 are determined in the same manner as described above.

After determining the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts in the bodily coordinate system Cp by the means 30 for calculating the position of the center of gravity of each portion, the arithmetic processing unit 16 executes the processing by the bodily center of gravity position calculating means 31 to determine the position (xg, zg) of the bodily center of gravity G0 of the human being 1 in the bodily coordinate system Cp, using the data of the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts and the data of the weights of the rigid corresponding parts.

If the position of the center of gravity G3 and the

weight of the waist 3 in the bodily coordinate system Cp are denoted by (x3, z3) and m3, respectively, the position of the center of gravity G4 and the weight of the body 38 are denoted by (x4, z4) and m4, respectively, the position

5 of the center of gravity G1 and the weight of the thigh 9 of the leg 2, which is located at left as observed in the advancing direction of the human being 1, are denoted by (x1L, z1L) and m1L, respectively, the position of the center of gravity G2 and the weight of the crus 11 of the

10 leg 2 are denoted by (x2L, z2L) and m2L, respectively, the position of the center of gravity G1 and the weight of the thigh 9 of the leg 2 at right are denoted by (x1R, z1R) and m1R, respectively, the position of the center of gravity G2 and the weight of the crus 11 of the leg 2 are

15 denoted by (x2R, z2R) and m2R, respectively, and the weight of the human being 1 is denoted by M (=m1L+m2L+m1R+m2R+m3+m4), then the position (xg, zg) of the bodily center of gravity G0 of the human being 1 in the bodily coordinate system Cp will be determined by

20 Equation (9) given below:

$$xg = (m1L \cdot x1L + m1R \cdot x1R + m2L \cdot x2L + m2R \cdot x2R$$
$$+ m3 \cdot x3 + m4 \cdot x4) / M$$
$$zg = (m1L \cdot z1L + m1R \cdot z1R + m2L \cdot z2L + m2R \cdot z2R$$
$$+ m3 \cdot z3 + m4 \cdot z4) / M$$

25 ... ... (9)

After carrying out the processing of the bodily center of gravity position calculating means 31, the

arithmetic processing unit 16 further carries out the
processing of the bodily center of gravity acceleration
calculating means 34, the processing of the ankle position
calculating means 32, and the processing of the MP
5 position calculating means 33.

In this case, in the processing of the bodily
center of gravity acceleration calculating means 34, first,
the two-level differential value of the position (xg, zg)
of the bodily center of gravity G0 in the bodily
10 coordinate system Cp, that is, the acceleration $^{T}(d^2xg/dt^2,$
$d^2zg/dt^2)$ of the bodily center of gravity G0 with respect
to the origin 0 of the bodily coordinate system Cp, is
determined, using the time-series data of the position (xg,
zg) of the bodily center of gravity G0 in the bodily
15 coordinate system Cp determined by the bodily center of
gravity position calculating means 31 for each cycle time
mentioned above. Then, a vector sum of the acceleration
$^{T}(d^2xg/dt^2, d^2zg/dt^2)$ and the acceleration $a_0=^{T}(a_0x, a_0z)$ in
the absolute coordinate system Cf of the origin 0 of the
20 bodily coordinate system Cp determined by the reference
acceleration measuring means 28 is determined, thereby
determining an acceleration $a=^{T}(ax, az)$ of the bodily
center of gravity G0 in the absolute coordinate system Cf.

In the processing of the ankle position calculating
25 means 32, first, the position of the ankle joint 12 of
each leg 2 in the bodily coordinate system Cp is
determined by the same processing as that of the means 30

for calculating the position of the center of gravity of each portion from the current values of the data of the inclination angles θc and θd of the thigh 9 and the crus 11 of each leg 2 determined by the leg posture calculating 5   means 29, the current value of the data of the inclination angle θb of the waist 3 determined by the waist inclination angle measuring means 27, and the data of the sizes (lengths) of the thigh 9 and the crus 11. Specifically, referring to Fig. 4, regarding the leg 2 10   located on the left side in Fig. 4, if the length of the crus 11 (the length from the center of the knee joint 10 to the center of the ankle joint 12) is denoted by Ld, then the coordinate (x12, z12) of the position of the ankle joint 12 in the bodily coordinate system Cp will be 15   (Lc·sinθc+Ld·sinθd, -Lc·cosθc-Ld·cosθd)(where θc<0, θd<0 in Fig. 4). The same applies to the other leg 2.

      Furthermore, the positional vector ^{T}(x12-xg, z12-zg) of the ankle 12 of each leg 2 with respect to the bodily center of gravity G0, that is, ΔXf, ΔZf, ΔXr and ΔZr in 20   the above Equation (5), is determined from the position (x12, z12) in the bodily coordinate system Cp of the ankle joint 12 and the current value of the data of the position (xg, zg) of the bodily center of gravity G0 in the bodily coordinate system Cp determined by the bodily center of 25   gravity position calculating means 31.

      In the processing of the MP position calculating means 33, the position of the MP joint 13a (more

specifically, the position in the x-axis direction in the
bodily coordinate system Cp) is determined as follows.
Referring to Fig. 5, in the present embodiment, a distance
$\Delta xmp0$ in the horizontal direction (the x-axis direction)

5   between the ankle joint 12 and the MP joint 13a in the
state wherein the human being 1 is upright stationary (in
the state wherein the human being 1 is standing upright on
a horizontal floor A, having substantially the entire
surface of the sole of the foot 14 of each leg 2 in

10   contact with the floor A) is actually measured beforehand
and retained in a memory in the arithmetic processing unit
16.   The distance $\Delta xmp0$ may be actually measured and
retained in a memory separately for each leg 2, or it may
be actually measured only on one leg 2 and shared for both

15   legs 2 and 2.

In general, the horizontal distance between the
ankle joint 12 and the MP joint 13a while the human being
1 is in motion, such as level-ground walking, is
approximately equal to the aforesaid distance $\Delta xmp0$ in the

20   upright stationary state of the human being 1.
Accordingly, in the present embodiment, the position (the
position in the x-axis direction) of the MP joint 13a is
determined as the position apart from the ankle joint 12
by the aforesaid distance $\Delta xmp0$ in the x-axis direction.

25   Specifically, the value obtained by adding the distance
$\Delta xmp0$ to an x-axis coordinate component $x12$ of the current
value of the position $(x12, z12)$ of the ankle joint 12 in

the bodily coordinate system Cp obtained by the ankle

position calculating means 32 is determined as the

position of the MP joint 13a in the x-axis direction in

the bodily coordinate system Cp.

5   Next, the arithmetic processing unit 16 executes

the processing of the floor reaction force acting point

estimating means 38 and the processing of the floor

reaction force estimating means 39. In the processing of

the floor reaction force acting point estimating means 38,

10   a floor reaction force acting point related to each leg 2

in contact with the ground (the point at which total floor

reaction force acting on an in-contact-with-the-ground

place of the foot 13 is considered to concentrate) is

estimated as described below. First, detection signals of

15   the ground contact sensors 51f and 51r of each leg 2 are

determined, and if one of the ground contact sensors 51f

and 51r outputs an ON signal, then it is determined that

the leg 2 is in contact with the ground. And, on the leg

2 in contact with the ground, the position of a floor

20   reaction force acting point in the x-axis direction (the

horizontal position in the advancing direction of the

human being 1) is determined on the basis of the

combination of ON/OFF of the ground contact sensors 51f

and 51r of the leg 2 and the relative positional

25   relationship (specifically, the relative positional

relationship in the x-axis direction) among the ankle

joint 12 and the MP joint 13a of the leg 2 and the bodily

center of gravity G0.

More detailedly, referring to Fig. 6 (a), if the directly below ankle ground contact sensor 51r outputs an ON signal, whereas the directly below MP ground contact sensor 51f is OFF, then it is regarded that a floor reaction force acting point exists vertically immediately below the ankle joint 12, and the position of the ankle joint 12 in the x-axis direction is determined as the position of the floor reaction force acting point in the x-axis direction (the horizontal position in the advancing direction of the human being 1). This means that the state wherein the directly below ankle ground contact sensor 51r and the directly below MP ground contact sensor 51f are ON and OFF, respectively, as described above is a state wherein the foot 13 of the leg 2 provided with the ground contact sensors 51r and 51f is in contact with a floor A at a place adjacent to the heel thereof. And, in such a state, the floor reaction force acting point of the leg 2 is positioned substantially right below (vertically below) the ankle joint 12. Thus, if the directly below ankle ground contact sensor 51r and the directly below MP ground contact sensor 51f are ON and OFF, respectively, then the position of the floor reaction force acting point in the x-axis direction of the leg 2 in contact with the ground is determined as described above. Fig. 6 (a) schematically shows only one leg 2 in contact with the ground, and the other leg is not shown. The same will

apply to Fig. 6 (b) and Figs. 7 (a) to (c) to be explained below.

Further, referring to Fig. 6 (b), if the directly below ankle ground contact sensor 51r is OFF, whereas the directly below MP ground contact sensor 51f outputs an ON signal, then it is regarded that a floor reaction force acting point exists vertically immediately below the MP joint 13a, and the position of the MP joint 13a in the x-axis direction is determined as the position of the floor reaction force acting point in the x-axis direction. This means that the state wherein the directly below ankle ground contact sensor 51r and the directly below MP ground contact sensor 51f are OFF and ON, respectively, is a state wherein the foot 13 of the leg 2 provided with the ground contact sensors 51r and 51f is in contact with the floor A at a place adjacent to the toe thereof. And, in such a state, the floor reaction force acting point of the leg 2 is positioned substantially right below (vertically below) the MP joint 13a. Thus, if the directly below ankle ground contact sensor 51r and the directly below MP ground contact sensor 51f are OFF and ON, respectively, then the position of the floor reaction force acting point in the x-axis direction of the leg 2 in contact with the ground is determined as described above.

The method for estimating the position of a floor reaction force acting point in the x-axis direction in the case of the combination of ON/OFF of the ground contact

sensors 51r and 51f corresponding to Figs. 6 (a) and (b),
respectively, does not depend on the mutual positional
relationship among the bodily center of gravity G0, the
ankle joint 12, and the MP joint 13a.

5   Meanwhile, if both the directly below ankle ground
contact sensor 51r and the directly below MP ground
contact sensor 51f output ON signals, then the position of
a floor reaction force acting point in the x-axis
direction is further estimated on the basis of the
10   relative positional relationship among the bodily center
of gravity G0, the ankle joint 12, and the MP joint 13a
(specifically, the relative positional relationship in the
x-axis direction of the bodily coordinate system Cp).
More detailedly, if the bodily center of gravity G0 is
15   positioned behind the ankle joint 12 (if the ankle joint
12 is positioned before the bodily center of gravity G0)
as shown in Fig. 7 (a), then it is assumed that the floor
reaction force acting point exists vertically directly
below the ankle joint 12, and the position of the ankle
20   joint 12 in the x-axis direction is determined as the
position of the floor reaction force acting point in the
x-axis direction. In other words, in a state wherein the
ankle joint 12 of a leg 2 in contact with the ground is
located before the bodily center of gravity G0, the floor
25   reaction force related to the leg 2 is concentrated in a
place adjacent to the heel of the foot 13. In such a
state, the floor reaction force acting point of the leg 2

is positioned substantially directly below the ankle joint
12. Hence, if the ankle joint 12 is positioned before the
bodily center of gravity G0, as shown in Fig. 7 (a), the
x-axis position of the floor reaction force acting point
5   of the leg 2 in contact with the ground is determined as
described above.

     Further, if the bodily center of gravity G0 is
located between the MP joint 13a and the ankle joint 12 in
the x-axis direction as shown in Fig. 7 (b), then it is
10   assumed that the floor reaction force acting point exists
vertically directly below the bodily center of gravity G0,
and the position of the bodily center of gravity G0 in the
x-axis direction is determined as the position of the
floor reaction force acting point in the x-axis direction.
15   This means that if the position of the bodily center of
gravity G0 in the x-axis direction is between the MP joint
13a and the ankle joint 12 of the leg 2 in contact with
the ground, the floor reaction force related to the leg 2
concentrates in the vicinity of a spot vertically below
20   the bodily center of gravity G0. Thus, if the position of
the bodily center of gravity G0 in the x-axis direction is
between the MP joint 13a and the ankle joint 12 of the leg
2 in contact with the ground, as shown in Fig. 7 (b), the
x-axis position of the floor reaction force acting point
25   of the leg 2 in contact with the ground is determined as
described above.

     Further, if the bodily center of gravity G0 is

positioned before the MP joint 13a (if the MP joint 13a is positioned behind the bodily center of gravity G0) as shown in Fig. 7 (c), then it is assumed that the floor reaction force acting point exists vertically directly

5   below the MP joint 13a, and the position of the MP joint 13a in the x-axis direction is determined as the position of the floor reaction force acting point in the x-axis direction.   In other words, in a state wherein the MP joint 13a of a leg 2 in contact with the ground is located

10 behind the bodily center of gravity G0, the floor reaction force related to the leg 2 is concentrated in a place adjacent to the toe of the foot 13.   In such a state, the floor reaction force acting point of the leg 2 is positioned substantially directly below the MP joint 13a.

15 Hence, if the MP joint 13a is positioned behind the bodily center of gravity G0, as shown in Fig. 7 (c), the x-axis position of the floor reaction force acting point of the leg 2 in contact with the ground is determined as described above.

20   The x-axis position of the floor reaction force acting point of each leg 2 in contact with the ground is estimated by the processing of the floor reaction force acting point estimating means 38 explained above.   The relationship among the combinations of ON and OFF of both

25 ground contact sensors 51r and 51f, the relative positional relationship among the bodily center of gravity G0, the ankle joint 12 and the MP joint 13a, and the

position of a floor reaction force acting point in the x-axis direction obviously applies to a case where the human being 1 is walking on a flat ground and generally applies also to a case where, for example, the human being 1 sits onto a chair or rises from the chair, and a case where the human being 1 walks on a staircase or a slope.

Further in the processing of the floor reaction force acting point estimating means 38, the vertical position (the position in the z-axis direction) of the floor reaction force acting point of each leg 2 in contact with the ground is determined as described below. First, on each leg 2 in contact with the ground, the distance between the ankle joint 12 of the leg 2 and a ground contact surface (the floor A) is grasped. In this case, according to the present embodiment, a value stored and retained beforehand in the arithmetic processing unit 16 is grasped as the distance between the ankle joint 12 and the ground contact surface (the floor A)(hereinafter referred to as "the distance between the ankle joint and the ground contact surface"). To be more specific, referring to Fig. 5 mentioned above, a distance Ha from the center of the ankle joint 12 to the floor A surface (the ground contact surface) when the human being 1 is in the upright stationary state (hereinafter referred to as "the ankle joint reference height Ha") is actually measured in advance and retained in a memory of the arithmetic processing unit 16. The ankle joint reference

height Ha may be actually measured for each leg 2

separately, or only one leg 2 may be actually measured and

retained in a memory to be shared for both legs 2. Thus,

the ankle joint reference height Ha stored and retained as

5   described above is grasped as the distance between the

ankle joint and the ground contact surface.

As discussed above, the distance between the ankle

joint and the ground contact surface is grasped, and then

the vertical position (the position in the z-axis

10   direction) of a floor reaction force acting point is

determined as the position vertically apart downward from

the position of the ankle joint 12 by the grasped distance

between the ankle joint and the ground contact surface.

In other words, the vertical position (the position in the

15   bodily coordinate system Cp) of the floor reaction force

acting point is determined as the value obtained by

subtracting the distance between the ankle joint and the

ground contact surface, which has been grasped as

described above, from the value of the z-axis component of

20   the position of the ankle joint 12 (the upward direction

being defined as the positive direction of the z-axis).

According to the present embodiment, in order to

calculate a joint moment by a joint moment estimating

means 40, which will be discussed hereinafter, the

25   position of the floor reaction force acting point in the

bodily coordinate system Cp decided as described above

(xz-coordinate component) is further converted into a

position defined, using the position of the ankle joint 12 in the bodily coordinate system Cp calculated by the ankle position calculating means 32 as its reference. More specifically, the estimated position of a floor reaction

5   force acting point is determined by conversion into a positional vector based on the position of the ankle joint 12 as the reference (hereinafter referred to as "the floor reaction force acting point vector").

By the processing of the floor reaction force

10   acting point estimating means 38 explained above, the floor reaction force acting point vectors (the positions in the x-axis direction and the z-axis direction) based on the ankle joint 12 are estimated on each leg 2 in contact with the ground.

15   In the processing of the floor reaction force estimating means 39, if the motion mode of the leg 2 determined at the current cycle time by the leg motion determining means 25 is the single stance state, then the estimated value of the floor reaction force $F={}^{T}(Fx, Fz)$

20   acting on the leg 2 in contact with the ground is determined according to the above Equation (2) from the values of the weight M of the human being land the gravity acceleration g (these are stored in the arithmetic processing unit 16 beforehand) and the current value of

25   the acceleration $a={}^{T}(ax, az)$ of the bodily center of gravity G0 in the absolute coordinate system Cf determined by the bodily center of gravity acceleration calculating

means 34. In this case, the floor reaction force acting
on the leg 2 not in contact with the ground (the free leg
2) is $^T(0, 0)$.

If the motion state of the leg 2 determined at the
current cycle time by the leg motion determining means 25
is the double stance state, then the estimated values of
the floor reaction forces Ff= ^{T}(Ffx, Ffz) and Fr= ^{T}(Frx,
Frz) of the individual legs 2 are determined according to
the above Equation (5) from the weight M of the human
being 1 and the gravity acceleration g, the current value
of the acceleration a=^{T}(ax, az) of the bodily center of
gravity G0 in the absolute coordinate system Cf determined
by the bodily center of gravity acceleration calculating
means 34, and the data of the current values of the
positions of the ankle joints 12 of the individual legs 2
relative to the bodily center of gravity G0 determined by
the ankle position calculating means 32 (the current
values of data of ΔXf, ΔZf, ΔXr, and ΔZr of Equation (5)).

Meanwhile, the arithmetic processing unit 16
carries out the processing of the means 35 for calculating
the acceleration of each portion of a leg and the means 36
for calculating the angular acceleration of each portion
of a leg in parallel to the processing of the bodily
center of gravity position calculating means 31, the
bodily center of gravity acceleration calculating means 34,
the ankle position calculating means 32, the MP position
calculating means 33, the floor reaction force acting

point estimating means 38, and the floor reaction force estimating means 39 described above.

In this case, in the processing of the means 35 for calculating the acceleration of each portion of a leg, as in the processing of the bodily center of gravity acceleration calculating means 34, first, the two-level differential values of the positions of the centers of gravity G1 and G2 of the thigh 9 and the crus 11 in the bodily coordinate system Cp, that is, the accelerations of the centers of gravity G1 and G2 of the thigh 9 and the crus 11 in the bodily coordinate system Cp (the accelerations relative to the origin 0 of the bodily coordinate system Cp), are determined, using the time-series data of the positions of the centers of gravity G1 and G2 of the thigh 9 and the crus 11, which are rigid corresponding parts of the legs 2 in the bodily coordinate system Cp determined by the means 30 for calculating the position of the center of gravity of each portion at each cycle time. Then, the vector sum of the aforesaid accelerations and the acceleration $a_0 = {}^T(a_0 x, a_0 z)$ in the absolute coordinate system Cf of the waist 3 obtained by the reference acceleration measuring means 28 is determined, thereby determining the accelerations of the thigh 9 and the crus 11, respectively, in the absolute coordinate system Cf (more specifically, the coordinate components of the accelerations in the absolute coordinate system Cf).

In the processing of the means 36 for calculating
the angular acceleration of each portion of a leg, the
time series data of the inclination angles θc and θd of
the thigh 9 and the crus 11 of each leg 2 obtained by the

5   leg posture calculating means 29 for each cycle time is
used to determine the two-level differential values of the
inclination angles θc and θd of the thigh 9 and the crus
11, that is, the angular accelerations of the thigh 9 and
the crus 11, respectively.

10   Next, the arithmetic processing unit 16 executes
the processing of the joint moment estimating means 40 to
determine the moments acting on the knee joint 10 and the
hip joint 8 of each leg 2. This processing is carried out
on the basis of a so-called inverse dynamics model by

15   using the current values of the data determined by the
floor reaction force estimating means 39, the means 35 for
calculating the acceleration of each portion of a leg, the
means 36 for calculating the angular acceleration of each
portion of a leg, the floor reaction force acting point

20   estimating means 38, and the leg posture calculating means
29, respectively. The inverse dynamics model uses an
equation of motion related to a translational motion and
the equation of motion related to a rotational motion of
each rigid corresponding part of the human being 1 to

25   determine moments acting on joints in order, beginning
with a joint closest to a floor reaction force acting
point. In the present embodiment, the moments acting on

the knee joint 10 and the hip joint 8 of each leg 2 are determined in order.

To be more specific, referring to Fig. 8, first, regarding the crus 11 of each leg 2, the force acting on
5   the ankle joint 12 of the distal portion of the crus 11 (the joint reaction force), the force acting on the portion of the knee joint 10 of the crus 11 (the joint reaction force), and the translational acceleration of the center of gravity G2 of the crus 11 are denoted by $^T(F_1x,$
10   $F_1z)$, $^T(F_2x, F_2z)$, and $^T(a_2x, a_2z)$, respectively, according to the component notation in the absolute coordinate system Cf, and the weight of the crus 11 is denoted by m_2. At this time, the equation of motion related to the translational motion of the center of gravity G2 of the
15   crus 11 will be the following equation (10):

$$^T(m_2 \cdot a_2x, m_2 \cdot a_2z) = {}^T(F_1x - F_2x, F_1z - F_2z - m_2 \cdot g)$$

therefore,

$$^T(F_2x, F_2z) = {}^T(F_1x - m_2 \cdot a_2x, F_1z - m_2 \cdot a_2z - m_2 \cdot g)$$

$$\text{... ... (10)}$$

20   The acceleration $^T(a_2x, a_2z)$ of the center of gravity G2 of the crus 11 is determined by the means 35 for calculating the acceleration of each portion of a leg. The joint reaction force $^T(F_1x, F_1z)$ acting on the ankle joint 12 of the distal portion of the crus 11 is
25   approximately equal to the estimated value of the floor reaction force determined by the floor reaction force estimating means 39 on the leg 2 having the crus 11.   To

be more specific, in a single stance state, if the leg 2

is in contact with the ground, then the joint reaction

force $^T(F_1x, F_1z)$ is the floor reaction force $^T(Fx, Fz)$

determined according to the above Equation (2). If the

5   leg 2 is a free leg, then $^T(F_1x, F_1z) = {}^T(0, 0)$. In a double

stance state, if the leg 2 is the leg at the rear side

relative to the advancing direction of the human being 1,

then the joint reaction force $^T(F_1x, F_1z)$ is the floor

reaction force $^T(Frx, Frz)$ of the above Equation (5),

10   whereas if the leg 2 is at the front side, then it is the

floor reaction force $^T(Ffx, Ffz)$ of the above Equation (5).

Thus, the joint reaction force $^T(F_2x, F_2z)$ acting on

the knee joint 10 of each leg 2 is determined according to

the above Equation (10) from the data of the acceleration

15    $^T(a_2x, a_2z)$ of the center of gravity G2 of the crus 11

determined by the means 35 for calculating the

acceleration of each portion of a leg, the data of the

floor reaction force $(={}^T(F_1x, F_1z))$ determined by the floor

reaction force estimating means 39, the data of the weight

20   m_2 of the crus 11 determined in advance, and the value of

the gravity acceleration g.

Referring to Fig. 8, the moment acting on the ankle

joint 12 of the distal portion of the crus 11 is denoted

by M_1, the moment acting on the portion of the knee joint

25   10 of the crus 11 is denoted by M_2, the inertial moment

about the center of gravity G2 of the crus 11 is denoted

by I_{G2}, and the angular acceleration about the center of

gravity G2 of the crus 11 is denoted by α_2. In association with Fig. 4 mentioned above, if the distance between the center of gravity G2 of the crus 11 and the center of the knee joint 10 is denoted by t2, and the

5 distance between the center of gravity G2 of the crus 11 and the ankle 12 is denoted by t2' (=Ld-t2), then the equation of motion related to the rotational motion about the center of gravity G2 of the crus 11 will be Equation (11) shown below:

10 $$I_{G2} \cdot \alpha_2 = M_1 - M_2 + F_1 x \cdot t2' \cdot \cos\theta d - F_1 z \cdot t2' \cdot \sin\theta d$$

$$+ F_2 x \cdot t2 \cdot \cos\theta d - F_2 z \cdot t2 \cdot \sin\theta d$$

therefore,

$$M_2 = M_1 - I_{G2} \cdot \alpha_2 + F_1 x \cdot t2' \cdot \cos\theta d - F_1 z \cdot t2' \cdot \sin\theta d$$

$$+ F_2 x \cdot t2 \cdot \cos\theta d - F_2 z \cdot t2 \cdot \sin\theta d$$

15 $$\dots \dots (11)$$

where M_1 in Equation (13) denotes the moment obtained in terms of the outer product (vector product) of the floor reaction force acting point vector determined as described above by the floor reaction force acting point

20 estimating means 38 on the leg 2 having the crus 11 related to Equation (13) and the floor reaction force vector determined by the floor reaction force estimating means 39 on the leg 2. Further, α_2 denotes the angular acceleration of the crus 11 determined by the means 36 for

25 calculating the angular acceleration of each portion of a leg. Further, θd denotes the inclination angle of the crus 11 determined by the leg posture calculating means 29.

Further, $^T(F_1x, F_1z)$ denotes the estimated value of a floor reaction force determined by the floor reaction force estimating means 39 as described above. Further, $^T(F_2x, F_2z)$ is determined according to the above Equation (12).

Further, the inertial moment I_{G2} is determined together with the data or the like of the weight m_2 and size of the crus 11 and stored in the arithmetic processing unit 16 beforehand.

Accordingly, the moment M_2 acting on the knee joint 10 is determined by the above Equation (11) from the data of the estimated value of a floor reaction force obtained by the floor reaction force estimating means 39, the data of the estimated value of a floor reaction force acting point vector obtained by the floor reaction force acting point estimating means 38, the data of the angular acceleration α_2 of the crus 11 obtained by the means 36 for calculating the angular acceleration of each portion of a leg, the data of the inclination angle θd of the crus 11 obtained by the leg posture calculating means 29, the data of the joint reaction force $^T(F_2x, F_2z)$ determined according to the above Equation (10), and the data of the inertial moment I_{G2}, the size (Ld), and the position (t2) of the center of gravity G2 of the crus 11 determined in advance.

After determining the moment M_2 acting on the portion of the knee joint 10 of the crus 11 as described above, the joint moment estimating means 40 determines the

moment acting on the portion of the hip joint 8 of the thigh 9 by the same processing as the calculation processing therefor. The basic concept of this processing is the same as that of the technique for determining the

5   moment M_2 of the knee joint 10, so that detailed illustration and explanation will be omitted, an outline thereof being given below.

First, the joint reaction force $^T(F_3x, F_3z)$ acting on the portion of the hip joint 8 of the thigh 9 is

10   determined according to the following Equation (12) (equation having the same form as that of the above Equation (10)) based on the equation of motion related to the translational motion of the center of gravity G1 of the thigh 9 (refer to Fig. 4).

15    $$^T(F_3x, F_3z) = {}^T(F_2x - m_1 \cdot a_1x, \ F_2z - m_1 \cdot a_1z - m_1 \cdot g)$$

$$\ldots \ldots (12)$$

where $^T(F_2x, F_2z)$ denotes a joint reaction force of the knee joint 10 determined previously according to the Equation (10). Further, $^T(a_1x, a_1z)$ denotes an

20   acceleration (translational acceleration), in the absolute coordinate system Cf, of the center of gravity G1 of the thigh 9 determined by the means 35 for calculating the acceleration of each portion of a leg. Further, m_1 denotes the weight of the thigh 9 determined in advance,

25   and g denotes a gravitational acceleration.

Subsequently, a moment M_3 acting on the portion of the hip joint 8 of the thigh 9 is determined according to

Equation (13) given below (an equation of the same form as that of the above Equation (11)) on the basis of the equation of motion related to a rotational motion about the center of gravity G1 of the thigh 9.

$$M_3 = M_2 - I_{G1} \cdot \alpha_1 + F_2 x \cdot t1' \cdot \cos\theta c - F_2 z \cdot t1' \cdot \sin\theta c$$

$$+ F_3 x \cdot t1 \cdot \cos\theta c - F_3 z \cdot t1 \cdot \sin\theta c$$

$$\dots \dots (13)$$

M_2 denotes the moment of the knee joint 10 determined according to the above Equation (11), $^T(F_2 x, F_2 z)$ denotes a joint reaction force of the knee joint 10 determined according to the Equation (10), $^T(F_3 x, F_3 z)$ denotes a joint reaction force of the hip joint 8 determined according to the Equation (12), I_{G1} denotes an inertial moment about the center of gravity G1 of the thigh 9 determined in advance, α_1 denotes an angular acceleration of the thigh 9 determined by the means 36 for calculating the angular acceleration of each portion of a leg, and θc denotes an inclination angle of the thigh 9 determined by the leg posture calculating means 29. Further, t1 denotes the distance from the center of the hip joint 8 to the center of gravity G1 of the thigh 9 (refer to Fig. 4), and t1' denotes the distance from the center of knee joint 10 to the center of gravity G1 of the thigh 9 (L_c-t1 in Fig. 4), these being decided on the basis of the position of the center of gravity G1 and the size (length) of the thigh 9 determined in advance.

The processing explained above is successively

executed at each cycle time of the arithmetic processing

unit 16 to estimate, in real-time, the floor reaction

force acting on each leg 2 and the moments acting on the

knee joint 10 and the hip joint 8 of each leg 2.

5   Although detailed explanation in the present

specification will be omitted, the estimated values of the

moments of the knee joint 10 and the hip joint 8 that have

been determined are used for, e.g., controlling an

apparatus that aids the walking of the human being 1 (an

10   apparatus that includes an electric motor or the like

capable of imparting auxiliary torque to the knee joint 10

or the hip joint 8).

             Examples of the time-dependent changes in the

estimated value of a floor reaction force acting point

15   determined by the processing of the arithmetic processing

unit 16 described above are indicated by the solid lines

in Fig. 9 and Fig. 10.   Fig. 9 and Fig. 10 show, with the

solid lines, the time-dependent changes in a component in

the x-axis direction (a horizontal component in the

20   advancing direction) and a component in the z-axis

direction (a vertical component) of the estimated value of

a floor reaction force acting point of a leg 2 from the

moment the leg 2 comes in contact with the ground to the

moment it leaves the floor when the human being 1 is

25   walking on a level ground at a moving speed of, for

example, about 4.5 km/h.   In this case, the component in

the x-axis direction shown in Fig. 9 has been converted to

the absolute coordinate system Cf fixed to the floor A.
The component in the z-axis direction shown in Fig. 10 is
expressed in terms of a z-axis coordinate value
(corresponding to the vertical distance from the center of
5   the hip joint 8 to a floor reaction force acting point) in
the bodily coordinate system Cp. Fig. 9 and Fig. 10 also
show, with dashed lines, a component in the x-axis
direction and a component in the z-axis direction of a
floor reaction force acting point actually measured using
10   a force plate or the like. As seen in these Fig. 9 and
Fig. 10, the estimated values of the floor reaction force
acting points agree with actually measured values with
relatively good accuracy.

Regarding the component in the z-axis direction
15   shown in Fig. 10, the difference between the estimated
value and the actually measured value exhibits a
relatively large increase immediately before the leg 2
leaves the floor. This is because, in the present
embodiment, the vertical position (the position in the z-
20   axis direction) of the floor reaction force acting point
is determined with a fixed vertical distance between the
ankle joint 12 and the floor reaction force acting point
(being equal to the distance Ha between the ankle joint
and the ground contact surface in Fig. 5), so that the
25   error of the vertical position of the floor reaction force
acting point increases in such a state wherein the heel
side of the foot 13 floats from the floor A, as in the

case of immediately before the leg 2 leaves the floor.

Supplementally to Fig. 9, this figure, Fig. 9, also shows the calculated values of the positions of the MP joint 13a, the bodily center of gravity G0, and the ankle joint 12 in the x-axis direction (the values converted into the absolute coordinate system Cf). Since the position of a floor reaction force acting point in the x-axis direction in a level-ground walking mode is estimated as described above, in a period in which the bodily center of gravity G0 is located behind the ankle joint 12 (the period until time t1), the position of the floor reaction force acting point in the x-axis direction agrees with the position of the ankle joint 12 in the x-axis direction. In a period wherein the bodily center of gravity G0 is located between the ankle joint 12 and the MP joint 13a in the x-axis direction (the period from time t1 to t2), the position of the floor reaction force acting point in the x-axis direction agrees with the position of the bodily center of gravity G0 in the x-axis direction. Further, in a period wherein the bodily center of gravity G0 is located before the MP joint 13a (the period after time t2), the position of the floor reaction force acting point in the x-axis direction agrees with the position of the MP joint 13a in the x-axis direction.

Fig. 11 to Fig. 20 show, with solid lines, the time-dependent changes of the estimated values of the moments of the knee joint 10 and the hip joint 8. Fig. 11

and Fig. 12 show the knee joint moment and the hip joint

moment, respectively, determined by the arithmetic

processing of the arithmetic processing unit 16 when the

human being 1 performs level-ground walking at a moving

5   speed of, for example, about 4.5 km/h. Fig. 13 and Fig.

14 show the knee joint moment and the hip joint moment,

respectively, determined when the human being 1 walks down

a staircase, and Fig. 15 and Fig. 16 show the knee joint

moment and the hip joint moment, respectively, determined

10   when the human being 1 walks up a staircase. Further, Fig.

17 and Fig. 18 show the knee joint moment and the hip

joint moment, respectively, determined when the human

being 1 sits onto a chair, and Fig. 19 and Fig. 20 show

the knee joint moment and the hip joint moment,

15   respectively, determined when the human being 1 rises from

the chair. These Fig. 11 through Fig. 20 also indicate,

with dashed lines, the moments actually measured using a

torque meter or the like. As seen in these Fig. 11

through Fig. 20, the trend of the changes in the estimated

20   values of the moment exhibits good agreement with actually

measured values. Thus, it is understood that the

estimated positions of the floor reaction force acting

points determined in the present embodiment can be

determined with sufficiently proper accuracy in estimating

25   the joint moments of the legs 2.

As explained above, the present embodiment makes it

possible to estimate the position of a floor reaction

force acting point when the human being 1 is walking on a level ground, a staircase or a slope, or sitting onto a chair or rising from the chair, by a simple technique without using a plurality of types of correlation data or

5   the like to estimate floor reaction force acting points.

A second embodiment of the present invention will now be explained with reference to aforementioned Fig. 2 to Fig. 8 and Fig. 21. The present embodiment differs from the first embodiment only partly in construction and

10   processing; therefore, the constructions or functional parts that are identical to those of the first embodiment will be assigned the same reference numerals and drawings as those of the first embodiment, and the explanation thereof will be omitted.

15   Referring to Fig. 2, according to the present embodiment, in a human being 1, an ankle joint angle sensor 24 that outputs a signal corresponding to a bending angle $\Delta\theta e$ of an ankle joint 12 is attached to the ankle joint 12 of each leg 2, in addition to the devices

20   explained in the first embodiment. As in the knee joint angle sensor 23 or the like, the ankle angle sensor 24 is composed of a potentiometer, and secured to the ankle joint 12 through a belt or the like, which is not shown. Further, the ankle joint angle sensor 24 is connected to

25   an arithmetic processing unit 16 through a signal line, which is not shown, to input its outputs to the arithmetic processing unit 16.

Here, the bending angle $\Delta\theta d$ detected by each ankle joint angle sensor 24 denotes the angle formed by the line, which connects the center of the ankle joint 12 and the center of an MP joint 13a of a foot 13 linked to the ankle

5   joint 12, and the axis of a crus 11.

Referring to Fig. 3, in the arithmetic processing unit 16 in the present embodiment, an output of the above each ankle joint angle sensor 24 is received and supplied to an MP position calculating means 33. Further supplied

10   to the MP position calculating means 33 are the positions of the ankle joint 12 (the positions in the bodily coordinate system Cp) calculated by an ankle position calculating means 32 in the same manner as that in the first embodiment, and also an inclination angle θd of the

15   crus 11 calculated by a leg posture calculating means 29.

The construction except for that explained above is identical to the construction of the first embodiment.

The present embodiment having the construction described above differs from the first embodiment only in

20   the processing of the MP position calculating means 33 and the processing of a floor reaction force acting point estimating means 38 of the arithmetic processing unit 16. More specifically, the present embodiment is adapted to grasp the positions of the MP joint 13a more accurately

25   than the first embodiment does so as to achieve higher accuracy of estimating the positions of floor reaction force acting points than in the first embodiment. The

following will explain in detail the processing of the MP position calculating means 33 and the processing of the floor reaction force acting point estimating means 38 in the present embodiment.

5   In the processing of the MP position calculating means 33, the position of the MP joint 13a (more specifically, the positions in the x-axis direction and the z-axis direction in a bodily coordinate system Cp) is determined as follows by using detection data or the like

10   of the ankle joint angle sensor 24.

Referring to Fig. 21, a segment S connecting the center of the ankle joint 12 and the center of the MP joint 13a (hereinafter referred to as "the foot main line S") is assumed, the angle formed by the foot main line S

15   with respect to the vertical direction (the z-axis direction) (the inclination angle of the foot main line S) is denoted by θe, and the length of the foot main line S (the distance between the ankle joint 12 and the MP joint 13a) is denoted by Ls. At this time, a distance Δxmp in

20   the horizontal direction (the x-axis direction) and a distance Δzmp in the vertical direction (the z-axis direction) between the ankle joint 12 and the MP joint 13a, that is, a position $^T(\Delta xmp, \Delta zmp)$ of the MP joint 13a relative to the ankle joint 12 is given according to the

25   following Equation (14):

$$^T(\Delta xmp, \Delta zmp) = (Ls \cdot sin\theta e, Ls \cdot cos\theta e)$$

$$\dots \dots (14)$$

In this case, the foot 13 may be regarded as substantially a rigid body, and at this time, Ls takes a constant.

Further, the inclination angle θe of the foot main line S is given according to the following Equation (15), using the bending angle $\Delta\theta e$ of the ankle joint 12 detected by the ankle joint angle sensor 24 and the inclination angle θd of the crus 11 determined by the leg posture calculating means 29:

$$\theta e = \theta d - (180 - \Delta\theta e) \ \dots \ \dots \ (15)$$

In Equation (15), "degrees" is used as the unit of angles.

In the processing of the MP position calculating means 33, the inclination angle θe of the foot main line S is first determined according to the above Equation (15) from the current value of the data of the inclination angle θd of the crus 11 of each leg 2 determined by the leg posture calculating means 29, and the current value of the detection data of the bending angle $\Delta\theta e$ of the ankle joint 12 obtained from the ankle joint angle sensor 24 attached to the leg 2. Then, the position $^T(\Delta xmp, \Delta zmp)$ of the MP joint 13a relative to the ankle joint 12 is determined according to the above Equation (14) from the determined inclination angle θe and the length Ls of the foot main line S actually measured beforehand on the human being 1 and stored and retained in the arithmetic processing unit 16. Furthermore, the position of the MP

joint 13a in the bodily coordinate system Cp is determined by calculating the vector sum of the position $^T(\Delta xmp, \Delta zmp)$ and the position of the ankle joint 12 determined by the ankle position calculating means 32 (the position in the bodily coordinate system Cp) $^T(x12, z12)$.

5

In the processing of the floor reaction force acting point estimating means 38, the horizontal position (the position in the x-axis direction) of a floor reaction force acting point of each leg 2 in contact with the ground is determined by the same technique as that in the first embodiment. Therefore, the explanation of the processing for estimating the horizontal positions of floor reaction force acting points will be omitted.

10

Meanwhile, in the processing of the floor reaction force acting point estimating means 38, the technique for estimating the vertical position (the position in the z-axis direction) of the floor reaction force acting point of each leg 2 in contact with the ground is different from that in the first embodiment; the vertical position of a floor reaction force acting point is decided as follows. First, on each leg 2 in contact with the ground, the distance between the ankle joint 12 of the leg 2 and the ground contact surface (a floor A), that is, the distance between the ankle joint and the ground contact surface, is grasped. In this case, the method for grasping the distance between an ankle joint and a ground contact surface is decided, depending on whether the bodily center

15

20

25

of gravity G0 is located before or behind the MP joint 13a
in the x-axis direction. If the bodily center of gravity
G0 is located behind the MP joint 13a, then it is
generally considered that the bottom of the heel of a foot

5   13 is substantially in contact with the floor A or is
positioned at substantially the same height as the surface
of the floor A. In this case, therefore, the aforesaid
ankle joint reference height Ha actually measured when the
human being 1 is in an upright stationary state and stored

10   and retained beforehand in the arithmetic processing unit
16 (refer to Fig. 5) is grasped as the distance between
the ankle joint and the ground contact surface.

        If the bodily center of gravity G0 is located
before the MP joint 13a, then the heel of the foot 13 is

15   usually floating above the surface of the floor A. In
this case, the distance between the ankle joint and the
ground contact surface is calculated as follows.
Referring to the aforesaid Fig. 21, if the heel of the
foot 13 is floating above the surface of the floor A, then

20   the distance between the ankle joint and the ground
contact surface will be the sum of the vertical distance
Δzmp between the ankle joint 12 and the MP joint 13a and
the distance between the MP joint 13a and the ground
contact surface (the surface of the floor A). In this

25   case, the distance between the MP joint 13a and the ground
contact surface is substantially identical to a distance
Hb between the MP joint 13a and the surface of the floor A

(hereinafter referred to as "the MP joint reference height Hb") in a state wherein the human being 1 is standing in an upright posture with substantially the entire sole of the foot 13 in contact with the floor A (in the aforesaid

5   upright stationary state), as shown in Fig. 5. Hence, according to the present embodiment, the MP joint reference height Hb is actually measured together with the ankle joint reference height Ha beforehand and stored and retained in the arithmetic processing unit 16. And, if

10   the bodily center of gravity G0 is located before the MP joint 13a, then the sum of the vertical distance Δzmp between the ankle joint 12 and the MP joint 13a grasped from the positions of these joints in the bodily coordinate system Cp and the MP joint reference height Hb

15   is determined as the distance between the ankle joint and the ground contact surface.

The MP joint reference height Hb may be actually measured and retained in a memory for each foot 13, or the actually measured value of only one foot 13 may be shared

20   for both feet 13 and 13. In correspondence to the floor reaction force acting point estimating method in accordance with the present invention, the ankle joint reference height Ha and the MP joint reference height Hb correspond to a first basic vertical distance and a second

25   basic vertical distance, respectively.

After the distance between the ankle joint and the ground contact surface is grasped as described above, the

vertical position (the position in the z-axis direction)
of a floor reaction force acting point is determined as
the position vertically apart downward from the position
of the ankle joint 12 by the grasped distance between the

5   ankle and the ground contact surface in the same manner as
that in the first embodiment. In other words, the
vertical position (the position in the bodily coordinate
system Cp) of the floor reaction force acting point is
determined as the value obtained by subtracting the

10   distance between the ankle joint and the ground contact
surface, which has been grasped as described above, from
the value of the z-axis component of the position of the
ankle joint 12 (the upward direction being defined as the
positive direction of the z-axis).

15   In the present embodiment also, as in the first
embodiment, in order to calculate a joint moment by a
joint moment estimating means 40, the position in the
bodily coordinate system Cp of the floor reaction force
acting point decided as described above (xz-coordinate

20   component) is converted into a position defined using the
position of the ankle joint 12 in the bodily coordinate
system Cp calculated by the ankle position calculating
means 32 as its reference.

        The processing of the arithmetic processing unit 16

25   except for the MP position calculating means 33 and the
floor reaction force acting point estimating means 38
explained above is the same as that in the first

embodiment.

The present embodiment makes it possible to grasp the positions of the MP joint 13a (the positions in the x-axis direction and the z-axis direction) with relatively high accuracy, thus allowing the positions, particularly the vertical positions, of floor reaction force acting points to be estimated with higher accuracy than that in the first embodiment. As a result, the joint moments acting on the knee joint 10 and the hip joint 8 can be estimated also with higher accuracy than that in the first embodiment.

The distance between an ankle joint and a ground contact surface determined to estimate the vertical position of a floor reaction force acting point can be determined by a technique other than the techniques explained in the first embodiment and the second embodiment. For example, an optical distance measuring sensor, such as an infrared distance measuring sensor, is attached to an appropriate portion of the crus 11 of each leg 2 (specifically, the portion apart from the ankle joint 12 toward the knee joint 10 by a predetermined distance in the axial direction of the crus 11), and the distance in the axial direction of the crus 11 between the portion to which the distance measuring sensor has been attached and a floor surface (the ground contact surface of the leg 2) is measured. Then, from the measured distance and the inclination angle θd of the crus 11, the

vertical distance between the portion equipped with the

distance measuring sensor and the floor surface

(hereinafter referred to as "the distance between the

sensor and the floor surface") is calculated by geometric

5   computation (trigonometric function computation). Further,

from the distance between the portion equipped with the

distance measuring sensor and the ankle joint 12 (a fixed

value) and the inclination angle θd of the crus 11, the

vertical distance between the portion and the ankle joint

10   12 is determined by the trigonometric function computation,

and then the determined vertical distance is subtracted

from the aforesaid distance between the sensor and the

floor surface so as to determine the distance between the

ankle joint and the ground contact surface. Thus,

15   determining the distance between the ankle joint and the

ground contact surface makes it possible to accurately

estimate the vertical position of a floor reaction force

acting point without using the ankle joint angle sensor 24.

In this case, the horizontal position of a floor reaction

20   force acting point may be estimated using the same

technique as that of the first embodiment.

In the embodiments explained above, the examples,

in which the present invention has been applied to the

human being 1, have been explained; however, the present

25   invention can be applied also to a biped walking robot as

a biped walking mobile body.

Industrial Applicability

As is obvious from the above explanation, the present invention makes it possible to estimate a joint moment of a leg of a biped walking mobile body, such as a
5   human being, so that the estimated joint moment can be applied for controlling the operation of a walking aid apparatus or the like that aids the walking of a human being. For example, a part of the estimated joint moment may be generated by the walking aid apparatus so as to
10   conduct control for reducing load on the human being.